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C O N F I D E N T I A L

ENGINEERING REPORT

SECURITY INFORMATION

REPORT NO.: 175-H-4 DATE. 1/11/52

TITLE: PRELIMINARY DESIGN STUDY OF TIP-MOUNTED POWER PLANTS FOR THE MX-1660 HELICOPTER ROTOR SYSTEM

MODEL NO. COPY NO. REPRODUCIBLE

CONTRACT NO. AF 33(600)-15613

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1. SUMMARY

This report presents a summary of the results of preliminary design studies of power plant configurations for the MX-1660 helicopter rotor system.

On the basis of performance analysis, design layouts, weight analysis, stress analysis, as well as preliminary static test results, a power plant configuration consisting of four 12 inch nominal diameter ducted pulse-jet engines located at the tip of each rotor blade is considered to be capable of supplying the power required. This configuration is indicated to achieve a minimum specific fuel consumption of 4.0 and a significant degree of noise reduction effectiveness.

Results of a preliminary analysis of thrust augmentation by means of either fuel additives or afterburning indicate that significant improvements in power plant performance might be expected with such augmentation.

It is shown that the close inter-relation among tip mounted power plant configuration, rotor structural and power requirement characteristics and the airframe and power control systems make it mandatory that extremely close coordination and flexible design liaison be maintained during the design of these components in order to obtain the most-satisfactory, best-integrated end product -- the jet propelled rotor system.

Recommendations for future power plant development work are also presented.

2. INTRODUCTION

This report presents a summary of the results of power plant preliminary design studies accomplished in accordance with Items 1.1.0, 1.3.0 and 1.5.0 of Exhibit "A" of U. S. Air Forces Contract No. AF 33 (600)-15613. This contract covers the development of the Project MX-1660 helicopter rotor system including the rotor tip-mounted power plants.

In addition to the results of the preliminary design studies, this report also presents recommendations for future power plant development programs required to develop the engines suitable for this rotor system.

3. DISCUSSION

Preliminary design considerations of the rotor blades for Project MX-1660 rotor system, plus engine structural limitations, established the following rotor tip-mounted engine design conditions:

Rotor Radius - 42.5 ft. (to centerline of power plant)
Rotor Tip Velocity - 500 ft/sec.
No. of Rotor Blades - 4
Total Engine Net Thrust Required - 2700 lb (at sea level)
Engine Net Thrust Required - 675 lb per rotor blade.

Other power plant requirements are maximum thrust per unit frontal area, minimum weight, minimum specific fuel consumption and minimum cold drag.

The past application of rotary wing tip-mounted pulse-jet engines to helicopter rotor system propulsion has been for maximum power requirements of approximately 70 lb. per rotor blade at 325 ft/sec. tip speed and as a result it has been practicable to utilize single engine configurations. The relatively high power requirement of this rotor system would require single engines of approximately 25 inch diameter which is believed to be too large to be practicable; that is, the engine diameter would be so large that high temperature areas of the engine would approach "flat plates" which would be vulnerable to flat plate buckling failures at the "g" loadings imposed by operation at the tip of the rotor blades. In addition, even though the length/diameter ratio of such a single engine might be similar to that of tip-mounted engines presently used, the absolute length of such an engine would be prohibitive in this application; therefore, it is deemed advisable to power each blade of the MX-1660 rotor system with more than one pulse-jet engine. In view of the foregoing considerations it is estimated that the diameter of the engines should not exceed a dimension in the order of 12 inches.

By virtue of the large radius of the rotor blades for this rotor system, the design tip speed may be increased considerably over that used in the previous, small capacity, rotor systems and at the same time the engines will be subjected to relatively low centrifugal loadings, as previously mentioned. The resulting practicable tip speeds is estimated to be on the order of 500 ft/sec.

Test data, recently obtained, indicates that the basic pulse-jet engines presently retain good performance characteristics at speeds up to and including 500 ft/sec.; however, at tip speeds in excess of 500 ft/sec., the results of the theoretical analysis of References 1 and 2 have indicated that performance over and above that of the basic pulse-jet engine may be realized by enclosing the basic pulse-jet engine(s) in a duct incorporating an inlet diffuser and exhaust nozzle

It will be extremely important during the detail design of this, as well as with any other jet propelled helicopter rotor system that the requirements of the rotor, power plants and control systems be carefully and closely coordinated. Increases in power plant weight can affect the rotor structure and power requirements and, conversely, any change in the rotor configuration can affect the size and power requirements of the power plants. In order that the best-integrated, optimum rotor system be produced, the importance of this liaison cannot be over-emphasized.

For the foregoing reasons it is believed that an arrangement of multiple, ducted, pulse-jet engines is potentially best suited to power the MX-1660 helicopter rotor system. The analysis and test results in the subsequent sections of this report are presented to substantiate quantitatively this conclusion which has been arrived at qualitatively.

3.1 RESULTS OF PRELIMINARY DESIGN STUDIES

3.1.1 Estimated Performance Characteristics

As mentioned above, the analysis of References 1 and 2 have indicated that the ducted pulse-jet engine will provide performance superior to that of the basic pulse-jet engine at speeds of 500 ft/sec. and above. It is necessary, however, to convert these performance calculations to actual values of engine performance on the basis of existing rotary wing tip-mounted pulse-jet engine performance.

The experimental whirl test data presented in Figure 1 show that an unducted 7.5-inch diameter pulse-jet engine will produce a maximum specific thrust (based upon maximum engine cross sectional area and net thrust) of 35.5 lb/44.1 sq. in. = 0.81 lb/sq. in. at a tip velocity of 500 ft/sec.

The data in Figure 2 indicate that engines of approximately 12 inches diameter will produce a specific thrust which is approximately 26 percent greater than the smaller size (7.5-inch diameter) engines. Application of this scale-up factor yields a specific thrust of 0.81 x 1.26 = 1.02 lb/sq. inch.

It is anticipated that further component and applied development of the basic pulse-jet engine will (conservatively) improve the thrust performance by an amount in the order of approximately 15 percent; therefore, a specific thrust of 1.02 x 1.15 = 1.18 may be expected from the basic, unducted pulse-jet engine.

The results of the theoretical analysis of ducted pulse-jet engine performance, shown in Figure 5 of Reference 2, indicate that such a configuration will provide a 15 percent improvement in performance over and above that of the basic engine(s), therefore, ducting of the basic engine(s) would provide a specific thrust of 1.18 x 1.15 = 1.36 lb/sq/ inch.

Figure 3 shows the variation in specific thrust with tip speed for the ducted engine. This performance is based upon the analysis of Reference 2.

Practical limitations, plus test results described in a subsequent section of this report indicate that four basic pulse-jet engines per rotor blade should be used. The thrust of each of the basic pulse-jet engines would therefore be:

$$2700/4 \times 4 = 168.7 \text{ lbs.}$$

The size of the basic ducted pulse-jet engine(s) will then be:

$$168.7/1.36 = 124 \text{ sq. inch} = 12.6 \text{ inch diameter.}$$

Therefore, an assembly of four 12.6 inch diameter ducted pulse-jet engines per rotor blade will be required to power the MX-1660 helicopter rotor system.

The theoretical analysis of ducted pulse-jet engine performance as presented in References 1 and 2 indicates specific fuel consumption values of from 2.5 to 3.0 at 550 ft/sec. These values are believed to be more optimistic than should be used in conjunction with the conservative thrust performance arrived at by the foregoing analysis. Instead, it is believed more realistic and consistent to assume that the specific thrust performance improvement as indicated above will be achieved without a change in basic engine fuel flow. Referring back to the basic engine performance as shown in Figure 1, the peak thrust occurred at a fuel flow of 240 lb/hr. With the specific thrust performance of the larger, ducted engine and this fuel flow, the estimated specific fuel consumption (at maximum thrust) is:

$$240/44.1 \times 1.36 = 4.0 \text{ lb/hr/lb thrust}$$

The part throttle specific fuel consumption of the ducted pulse-jet engine is expected to vary in a manner similar to that of an unducted engine. Such specific fuel consumption variation is shown in Figure 4. This variation for one of the full scale pulse-jet engines of the ducted assembly in terms of thrust and fuel flow is shown in Figure 5.

The results of free jet tests of an actual ducted pulse-jet engine as presented in Reference 3 indicate that this configuration will have a cold drag coefficient of 0.36 at 500 ft/sec. This is somewhat higher than would be desirable. Very little variation in the drag coefficient with tip speed is anticipated.

All of the foregoing performance estimates are presented for standard sea-level conditions. The thrust performance at any other altitude can be determined by multiplying the ratio of the air density at any desired altitude to the density at sea-level conditions by the sea-level thrust. The specific fuel consumption is essentially constant for all altitudes. These altitude performance characteristics have been substantiated by actual static and whirl tests and the substantiating altitude static test data are presented in Reference 4.

3.1.2 Effects of Thrust Augmentation

The basic characteristics of the pulse-jet power plant are such that the minimum specific fuel consumption occurs at or very near maximum thrust and gradually increases with decreasing power (See Figure 4). If some means were provided to augment the thrust of the basic engines in order to obtain the maximum power required for the hovering ceiling condition, then the basic pulse-jet engine size could be reduced and the engines could be operated at higher percentages of peak power -- hence at better values of specific fuel consumption under cruising conditions. This would, in turn, increase the range of the helicopter.

The performance potential of two possible methods of ducted pulse-jet engine thrust augmentation were therefore investigated by means of the analysis developed and discussed in Appendix A and B of Reference 2.

The first method of thrust augmentation considered was the addition of magnesium to the usual hydrocarbon fuel. This fuel combination would be similar to that reported in Reference 5. Such a magnesium-hydrocarbon fuel conbination will, conservatively, yield a combustion temperature of 4000° R as compared with 3000° R for hydrocarbon fuel only. This increase in pulse-jet combustion temperatures would increase the ducted engine thrust 10 percent. This performance improvement in terms of specific fuel consumption variation is indicated in Figure 6.

On the basis of the additional combustion temperature alone, this method of thrust augmentation is not spectacular; however, it is believed possible that, due to the incandescent particles and/or the higher temperature, the rate of burning in the basic pulse-jet engine might be increased. This in turn would result in a very significant improvement in engine performance. For instance, it has been estimated (Reference 6) that if the burning time could be decreased from .021 sec. (approx. value at the present time) to .014 sec., the thrust performance of a given engine would be increased over 100 percent.

The second method of thrust augmentation considered was that of afterburning in the aft portion of the duct of the ducted pulse-jet engine combination. This condition would achieve maximum possible overall temperature rise and would effect an increase of approximately 30 percent in ducted engine peak thrust performance.

Figure 6 also presents the effect of this method of thrust augmentation on part throttle fuel consumption characteristics for the condition where the afterburner is used for from 80 to 100 percent of maximum power while the pulse-jets are maintained at peak power. The afterburner would then be cut out at below 80 percent maximum power and the remainder of the throttling range would be accomplished with the basic pulse-jets.

3.1.3 Basic Configurations Considered

The three multiple ducted configurations shown in Drawing Numbers 530050, 530051 and 530060 were the main ones considered in this preliminary design phase. It will be noted, that the basic pulse-jet engines shown in these drawings are 12.0-inch in diameter as compared with 12.6-inch diameter units indicated necessary by the foregoing performance analysis (without thrust augmentation). This is due to the fact that the design layouts were initiated prior to completion of the rotor system power required and subsequent engine size estimates. Due to the relatively small difference in size, it was not deemed practical at this stage to revise the power plant layout drawings.

The evaluation of the relative merits of the three configurations must take into account the information presented in subsequent sections of this report; therefore, no attempt is made to make a comparative evaluation in this section. Such an evaluation is indicated in Section 4. ("Summary of Preliminary Design Study Results".)

3.1.3.1 Radial "Cluster" Configuration

The configuration shown in Drawing No. 530050 arranges the four pulse-jet engines in pairs which are located above and below the horizontal centerline of the duct. Since the engines are located radially equidistant from the longitudinal axis of the duct, this configuration is hereinafter referred to as the "radial configuration."

A major structural member is located on the horizontal centerline of the duct. This member contains the basic rotor tip attach structure as well as providing a convenient point of attachment for the pulse-jet engines.

The cylindrical duct cross section used with this radial configuration offers greater rigidity with fewer reinforcing members than the other configurations considered. This in turn results in a lower weight.

Since this radial configuration is symmetrical about the horizontal centerline, it is conceivable that initial development of this full scale configuration could be accomplished using one-half of a complete assembly.

3.1.3.2 In-line Bank Configuration

The second configuration considered is shown in Drawing No. 530051 and it arranges the four pulse-jet engines side-by-side as close together as possible on the horizontal centerline of the ducted assembly. This configuration has been termed "in-line." A perspective sketch is shown in Figure 6A.

The basic structure of this in-line configuration consists of a box beam structure connecting the rotor tip to the fore and aft engine support structure.

The forward engine structural member ties each pulse-jet engine together at the forward end of the combustion chamber. This member also provides the support for the forward end of the outer duct and its inlet diffuser.

The aft structural member supports the pulse-jet engine tailpipes in a manner such that they are free to expand longitudinally. This aft member also ties the upper and lower sections of the duct together.

Since the duct portion of the in-line configuration has a considerable amount of flat plate area, longitudinal members are added between the upper and lower surfaces to provide a rigid assembly.

3.1.3.3 Submerged 90-degree Exhaust Configuration

The third power plant configuration considered consisted of arranging the four pulse-jets with their axes parallel to the spanwise axis of the rotor blade and submerging them in an airfoil section. The engine's tailpipes are ducted into a common exhaust and this exhaust is diverted 90° aft from the rotor axis. This exhaust duct is then enclosed by a duct incorporating an inlet diffuser and exhaust nozzle. This configuration was considered for the potentially low drag resulting from submerging the engines and due to the fact that the adverse effects of centrifugal loads on the engine tubes would be minimized.

Since the results of the 90° exhaust static tests, described in Section 3.1.6, were not encouraging and since it was believed that a relatively large amount of additional time and effort would need to be e expended in order to develop this configuration due to its departure from existing configurations, the preliminary design layout shown in Drawing No. 530060, was only partially completed. However, the basic advantages of this configuration as described above, indicate that it should receive further consideration in a longer range program as a possible arrangement for rotors having extremely high tip speeds.

3.1.4 Estimated Weight Characteristics

Presented below are the estimated weights of the radial (Drawing No. 530050) and the in-line (Drawing No. 530051) multiple ducted engine configurations.

WEIGHT OF RADIAL CONFIGURATION

Pulse-jet Engine Components

Valve Box and Valves	6.00	
Cowling	1.25	
Fuel and Air Ring Assembly	1.50	
Venturi	.90	
End Plate	3.60	
Transition	19.00	
Tailpipe	15.00	
Tailpipe Support	1.75	
Weld, Bolts, Gaskets, etc.	3.00	
Total Individual Engine Weight	52.00 lbs.	
Total Pulse-jet Engine Weight = 52.00 x 4		208.00 lbs.

Duct Components

Inlet Cowling	8.0	
Center Section Outer Skin	24.0	
Fwd. Section Inner Skin	14.0	
Aft. Section Inner Skin	10.0	
Exhaust Cowling	22.0	
Frames	13.0	
Stringers	3.5	
Angles and Clips	2.5	
Center Dividing Skins	12.0	
Total Duct Weight		109.00 lbs.

Support Structure

Main Tension Members	13.0	
Compression Member	10.0	
Engine Tie Members	6.0	
℄ Tension Tie	3.0	
Total Support Structure Weight		33.00 lbs.
Total Power Plant Weight		350.00 lbs.

WEIGHT OF IN-LINE CONFIGURATION

Pulse-Jet Engine Components		
Valve Box and Valves	6.00	
Cowling	1.25	
Fuel and Air Ring Assembly	1.50	
Venturi	.90	
End Plate	3.60	
Transition	19.00	
Tailpipe	15.00	
Tailpipe Support	1.75	
Weld, Bolts, Gaskets, etc.	3.00	
Total Individual Engine Weight	52.00 lbs.	
Total Pulse-Jet Engine Weight = 52.00 x 4		208.00 lbs.
Duct Components		
Inlet Cowling	8.0	
Center Section Outer Skin	23.5	
Center Section Inner Skin	18.5	
Exhaust Cowling	60.5	
Internal Stiffeners	6.0	
Fairing	5.0	
Total Duct Weight		121.00 lbs.
Support Structure		
Duct to Blade Attach Structure	38.0	
Forward Engine and Duct Tension Member	13.0	
Aft Engine & Duct Tension Member	12.0	
Total Support Structure Weight		63.00 lbs.
Total Power Plant Weight		392.00 lbs.

3.1.5 Estimated Structural Characteristics

Reference 8 presents an analysis of the ducted pulse-jet engine support yoke which would be used on either of the configurations discussed above. The engine is attached to this yoke by means of shear pins. The engine structure consists of a built-up sheet metal framework which supports the engine shells in such a manner as to permit them freedom for longitudinal thermal expansion and yet support them against the loads developed as a result of centrifugal force. The perspective cut-away of the structural support of the in-line duct of multiple engines is shown in Figure 6a. The radial cluster configuration, as described above, has a structural advantage over the in-line arrangement in that the engines above and below the rotor chord plane permits a structural shear member to pass between the upper and lower pair of engines and support each engine individually in a much more efficient manner.

A more detailed structural analysis will be made on each configuration during the detail design phase. In the preliminary design phase, however, only sufficient structural checks have been made to determine the feasibility of the configuration and approximate weights of the major components.

3.1.6 Results of Preliminary Static Tests

In view of the fact that an arrangement of several engines per rotor blade was deemed to be most advisable for use in powering the MX-1660 rotor system, static tests of multiple pulse-jet engine configurations were conducted in order to gain some insight into their performance characteristics. These tests were conducted with numbers of engines varying from one through five. An existing 6.75-inch diameter engine design was used in these tests.

The engine control panel used for these tests is shown in Figure 7.

The first phase of this test program was devoted to an individual static performance calibration of each of the five 6.75-inch diameter pulse-jet engines. A typical engine calibration curve is presented in Figure 8. The thrust data are presented in the form of thrust per unit frontal area of the engine(s) in order that the performance of the multi-engine configurations may be more directly comparable.

Results of initial tests of a dual engine configuration wherein the engines were located as closely together as possible indicated that the engines synchronized, that is, the engines operated at the same frequency but their explosions were phased 180° apart, and an appreciable reduction in fundamental frequency noise level was obtained. Quantitative data concerning this noise reduction are presented in Reference 7. It was decided to determine at what maximum distance the engines could be located with respect to each other and still retain synchronized operation. The results of these tests showed that two 6.75-inch diameter engines maintained positive synchronization at spacings up to 9.0-inches between the centerlines of the engines. At spacings greater than this the engines sometimes fired simultaneously and at other times they syncronized. There was no significant gain or loss in specific thrust with or without synchronized operation; however, as previously mentioned, the sound level of the engines was noticeably decreased with synchronized operation.

In view of the foregoing, results the balance of the in-line engine configurations, up to the total number of 5 as shown in Figure 5, 9 and 10, were tested with a spacing of 7.25 inch between the center-lines of the 6.75-inch maximum diameter engines (combustion chamber walls ½ inch apart). The results of these tests are shown in Figures 11 through 13 and qualitative comments concerning the various configurations are presented below.

Configuration.	Remarks
2 In-line Engines	Engines started easily and synchronized when fuel flow was stabilized; sound level relatively low.
3 In-line Engines	Engines started easily; non-synchronized sounding, outboard engine appeared to run rough and sound level higher than with 2 engines synchronized.
4 In-line Engines	Engines appeared to synchronize and operation was smooth; sound has a high pitch tone, engines started easily.
5 In-line Engines	Engines started easily; engine operation smooth with no pulsing noticed; appeared to have lower pitch than the 4 engine configuration.

The test data indicate that better part throttle specific fuel consumption is obtained by throttling all engines simultaneously than by step throttling of individual engines, however, in no case was the specific fuel consumption of multiple engines better than that of the basic, single engine.

Figure 14 presents the peak specific thrust variation as the number of engines was increased. This figure shows only a slight change in peak specific thrust with the change in the number of engines.

In view of the potential weight advantages of the radial engine configuration described in Section 3.1.4, it was deemed advisable to check the static performance of such a configuration. Four engines were mounted with 7.25 inches between their horizontal centerlines and 11.75 inches between their vertical centerlines. The data obtained from static tests of this configuration are presented in Figure 15. This arrangement appeared to be slightly better than its in-line counterpart from the stand-point of smoothness of operation, generally lower sound level, and a slight indication of better overall throttling characteristic.

The next static tests were keyed to the preliminary design consideration of the 90° exhaust configuration previously mentioned in Section 3.1.3. As with the previous, multiple engine tests basic 6.75-inch maximum diameter engines having a nominal static thrust rating of 34-35 pounds were used in these tests.

The static thrust vs. fuel flow characteristics of the various operable configurations are given in Figures 16 through 25 which are keyed to the configuration number assigned in the following brief discussion of each configuration:

Configuration I consisted of a single pulse-jet engine having a short radius 90° bend close to the end of the tailpipe as shown in Figure 26. This engine would not resonate. Failure to do so was probable due to the acoustic irregularities of the small radius bend in the tailpipe. This sharp bend could be expected to cause secondary reflected waves which are not in pahse with the primary reflected wave and hence, a resonant system will not be established.

Configuration II consisted of a single 6.75-inch diameter engine with a large radius 90° bend, the centerline of which was located at the mid-point of the tailpipe. This configuration is shown in Figure 27. This engine was operable, but as shown in Figure 16, the thrust was low and the specific fuel consumption high. The noise level did not sound particularly high. The reduced performance of this configuration as compared with the conventional 6.75-inch diameter engines could possibly be explained by reasoning similar to that presented for Configuration I.

The fact that resonance was established with this configuration, whereas it was not with the previous one, is probably due to the larger bend radius and also the longer straight section after the bend. Both of these factors would tend to reduce the interference effects of secondary reflections.

The family of engines hereinafter referred to as Configuration III is characterized by two identical parallel 6.75-inch diameter engines having their tailpipes directed into a common exhaust duct.

<u>Configuration III-A</u> consisted of dual engines having the tailpipes directed into a short exhaust duct as shown in Figure 28. This configuration would resonate when either of the engines were operated separately; however, it was impossible to run both engines simultaneously. The single engine thrust performance, as shown in Figure 17, was far below that of the basic conventional 6.75-inch diameter engine and resonance was erratic with single engine operation.

<u>Configuration III-B</u> was very similar to Configuration III-A, with the exception that the exhaust duct was extended several diameters as shown in Figure 29. This configuration resonated with one engine operating as well as with both engines running simultaneously. The static performance of this configuration is shown in Figures 18, 19 and 20. Qualitatively, when one engine was operating alone, the resonant

frequency appeared to be approximately the same as that of the basic 6.75-inch diameter engine; however, with both engines operating simultaneously the operating frequency was lowered noticeably. With simultaneous engine operation the engines apparently fired simultaneously with an operating frequency which it is believed would correspond to an engine having an over-all length of the engine plus the exhaust tailpipe.

Configuration III-C consisted of the long exhaust duct with a 90° bend added at the aft end as shown in Figure 30. Figures 21 and 22 present the static thrust performance of this configuration with the engines operated separately and with both engines operating simultaneously. As is shown in these figures very low values of thrust were measured. In fact, the measured maximum thrust with one engine operating alone was approximately equal to that with both engines operating.

Configuration III-D consisted of the components used in Configuration III-C, except that an exit nozzle having a minimum area of 0.444 times the exhaust duct area was added at the downstream end of the assembly. It was not possible to establish resonance with either single or the dual engines.

Configuration III-E consisted of a short exhaust duct with a 90° bend as shown in Figure 31. It was only possible to operate one engine at a time with this configuration and the resulting performance with each of the two engines is shown in Figure 23.

Configuration III-F was the same and III-E, except that the exhaust nozzle from Configuration III-D was added as shown in Figure 32. It was not possible to obtain resonant operation with this configuration.

Configuration III-G consisted of the short exhaust duct with the exit nozzle previously used. Again it was impossible to obtain resonant operation with this configuration which is shown in Figure 33.

Configuration III-H is shown in Figure 34 and it consisted of the long exhaust duct with the above mentioned exit nozzle. It was not possible to obtain resonant operation with this configuration.

Configuration III-I was identical to Configuration III-D, except that the exit nozzle area was increased to .70 times the area of the exhaust duct. It was not possible to obtain resonant operation with this configuration.

Configuration III-J was the same as Configuration III-I, except that the exhaust nozzle was divergent with an exit area of 1.78 times the exhaust duct area. With this configuration, it was possible to operate each pulse-jet singularly and both pulse-jets simultaneously. The test data obtained on this configuration are shown in Figures 24 and 25.

The frequency of operation with both pulse-jet engines resonating was much lower than with either operating alone. The two engines apparently fired simultaneously.

All of the foregoing configurations having convergent exhaust nozzles, failed to resonate. This is probably due to the nozzle restriction adversely affecting the reflected wave action such that operation was not possible. It will also be noted from the test data that in all the 90° and common exhaust configurations, thrust performance was not as high as that obtained with the basic, conventional pulse-jet engine.

4. SUMMARY OF RESULTS OF PRELIMINARY DESIGN STUDIES

The engine performance analysis presented herein indicates that multiple ducted pulse-jet engines consisting of 4 - 12.6-inch diameter engines per rotor blade will provide the power required for the MX-1660 helicopter rotor system. The specific fuel consumption at maximum power is indicated to be approximately 4.0 lbs/hr/lb of thrust.

Thrust augmentation may provide a means of improving the cruising range of a helicopter powered by multiple ducted pulse-jet power plants and at the same time reduce the size and weight of the engine assemblies.

The radial multiple ducted pulse-jet engine configuration has been indicated to be lighter than the in-line configuration.

The possibility of adverse aerodynamic effects resulting from yawed flow conditions existing in forward flight on the radial engine may favor the in-line configuration. It is believed that the more-nearly "two-dimensionel" characterictics of the in-line configuration will make it less sensitive to yawed flow in forward flight than the radial configuration. It is recommended that the configurations of both types of engines be continued during the detail design phase.

Preliminary static test data indicate that the performance of the radial configuration is slightly better than that of the in-line configurations. In either case, better noise control is achieved by using even numbers of engines. Better part throttle fuel consumption results when all of the engines of an assembly are throttled simultaneously as compared with the case where one, or more, engines are maintained at peak thrust and the remaining unit(s) are operated at part throttle.

The results of static tests of several 90° exhaust single and dual engine configurations were not encouraging.

5. RECOMMENDATIONS

5.1 DEVELOPMENT UNDER THE PRESENT CONTRACT

It is estimated, roughly, that the development effort required for the development of high power multiple ducted pulse-jet power plant increases in approximate proportion to the power increase obtained over previous development engines. The amount of funds presently allocated for power plant development under the present contract is believed therefore, to represent an insufficient amount to completely develop and fabricate the final power units for the test rotor.

At the present time it is believed that the greatest uncertainty in the performance estimation of multiple ducted pulse-jet engines is in evaluating the actual improvement in performance which can be obtained through the use of the aerodynamic ducting. It is believed that the greatest return by way of technological improvement for a given amount of funds available for power plant development under the present program can be obtained by investigating the effect of ducting on operative models approximately one-half full size. This technique permits the use of existing pulse-jet engines in determining the effects of the ducting, structural configuration and acoustical coupling on the engine performance before constructing the full-scale power units.

It is recommended, therefore, that the funds presently available for the development of power plants under the present contract be directed towards obtaining early substantiation of the theoretical pulse-jet engine performance improvement obtainable by ducting. In view of the limited funds available and present whirl test facility limitations, it is suggested that these development tests be conducted on scale operative models of approximately one-half full size.

It should be emphasized that the above recommended program implies that following completion of development tests on the scale model ducted pulse-jet assembly, there would be no funds available under the present contract allocations for the development either of a full-scale individual pulse-jet engine or fabrication of the final full-scale ducted multiple pulse-jet engine power unit for the test rotor.

5.2 SUPPLEMENTARY DEVELOPMENT PROGRAM

In view of the limited funds available for power plant development under the present contract, the supplementary development work indicated, very briefly, in the following sections is deemed necessary to insure that suitable power plants will be developed for the MX-1660 helicopter rotor system. It should be noted that this supplementary development work excludes that which is covered by "component" development work similar to that being accomplished under Contract No. AF 33(600)-5860, which it is assumed will be continued in order to contribute to the type of power plant required for this rotor system.

5.2.1 Basic Engine Development

The basic 12-inch nominal diameter engine development should be pursued in conjunction with its application to a full scale multiple ducted engine assembly suitable for propulsion of this particular rotor system.

5.2.2 Investigation of Ducted Engine Performance Parameters

It is anticipated that most of the basic ducted engine parameters affecting performance can be investigated most economically with operative models under a component development program; however, it is further anticipated that checks of these parameters as well as detailed development will be necessary with the full scale engines. Such checks and development work are therefore recommended as a part of the supplementary development work.

5.2.3 Structural Development

As with the ducted engine performance parameters, a limited amount of structural data may be obtained from the component development work with ducted models, however, a considerable amount of applied structural development of the specific configuration to be used on the MX-1660 rotor system is anticipated should be provided for in the supplementary development work.

5.2.4 Investigation of Thrust Augmentation Methods

It is strongly recommended that thrust augmentation methods similar to, but not limited to, those indicated in Section 3.1.2 of this report be the subject of further analysis and development test investigations.

5.2.5 Investigation of Methods of Reducing Cold Drag

Reference 9 shows the importance of the cold drag parasite area (which is the product of cold drag coefficient and power plant frontal area) on the autorotational characteristics of the subject rotor system. It is shown that the cold drag coefficient estimated in Paragraph 3.1.1 together with required frontal area of the pulse-jet power unit produces extremely high rates of descent. It is recommended that an early experimental verification of the cold drag coefficient be obtained and if the estimate is of the right order of magnitude, means of sufficiently reducing the deag coefficient be investigated. It is shown in Reference 9 that a target drag coefficient of more nearly .10 should be realized in order to botain satisfactory autorotational performance. Possible ways of reducing the cold drag coefficient include fairing of the inlet to shut-off the internal flow and/or fairing of the exit in order to reduce the high drag associated with the blunt aerodynamic base. Preliminary efforts should be directed towards determining the gains possible using these fairings and if these are reasonable, then further investigation should be made to determine the mechanical complexity of a device to accomplish this fairing automatically upon power plant shut-off.

5.2.6 Applications of Acoustical Model and Electrical Analogue Techniques

It is believed that the intelligent application of the new acoustical model and electrical analogue techniques already being developed under Contract AF 33(600)-5860 would enable the economical and rapid investigation of many problems associated with multiple ducted pulse-jet engines. For example, the problems associated with noise control, acoustical coupling, effect of ducting acoustics on engine performance, and many other items could be evaluated qualitatively if not quantitatively through the use of these techniques as applied to pulse-jet engines.

6. REFERENCES

Reference 1: Project Squid Report, CAL-36, "An evaluation of Potential Merits of Ducted Pulse-Jets", dated October 1949

Reference 2: Marquardt Aircraft Co. Report No. PP-7, "Theoretical Studies Associated with Pulse-Jet Engine Development", dated 26 September 1947.

Reference 3: Marquardt Aircraft Co. Report No. PP-11, "Summary Report Development Tests of Pulse-Jet Engines," dated 26 November 1947.

Reference 4: American Helicopter Co., Inc., Report No. 163-B-2, dated 20 December 1950, entitled "Altitude Performance and Operational Tests of Pulse-Jet Engines."

Reference 5: NACA Report No. RM-E-51C23, "Preliminary Evaluation of the Air and Fuel Specific Impulse Characteristics of Several Potential Ramjet Fuels", dated 2 May 1951.

Reference 6: Jet Propelled Missiles Panel Report No. 303, "The Intermittent Jet Engine."

Reference 7: American Helicopter Co., Inc., Report No. 163-K-3, dated 10 September 1952, "Results of Tests of Pulse-Jet Engine Noise Control Configurations".

Reference 8: American Helicopter Co., Inc., Report No. 175-H-7, dated 1 November 1952, entitled "Preliminary Structural Analysis of MX-1660 Helicopter Rotor System."

Reference 9: American Helicopter Co., Inc., Report No. 175-H-6, dated 1 November 1952, entitled "Preliminary Aerodynamic and Performance Analyses of MX-1660 Helicopter Rotor System."

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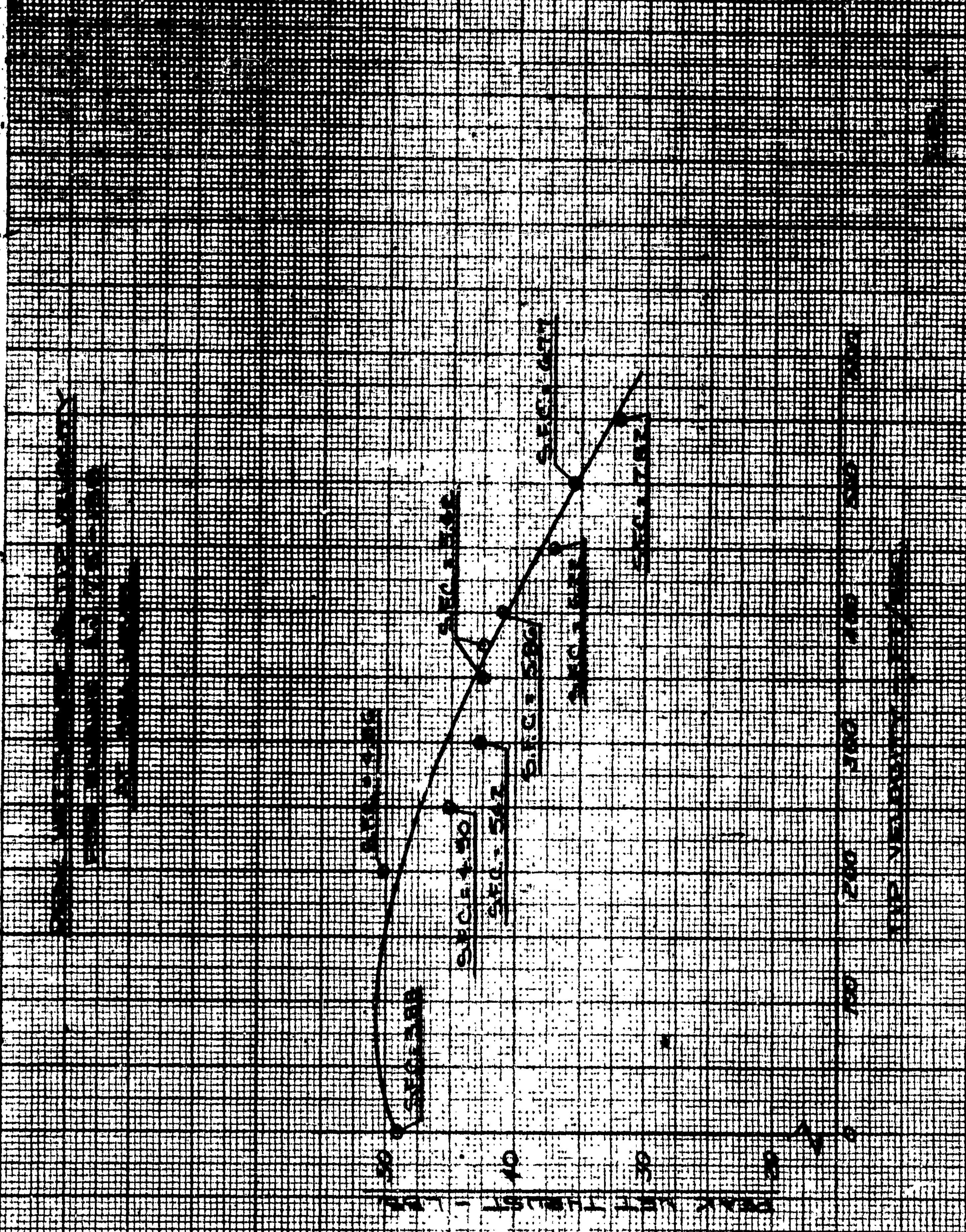

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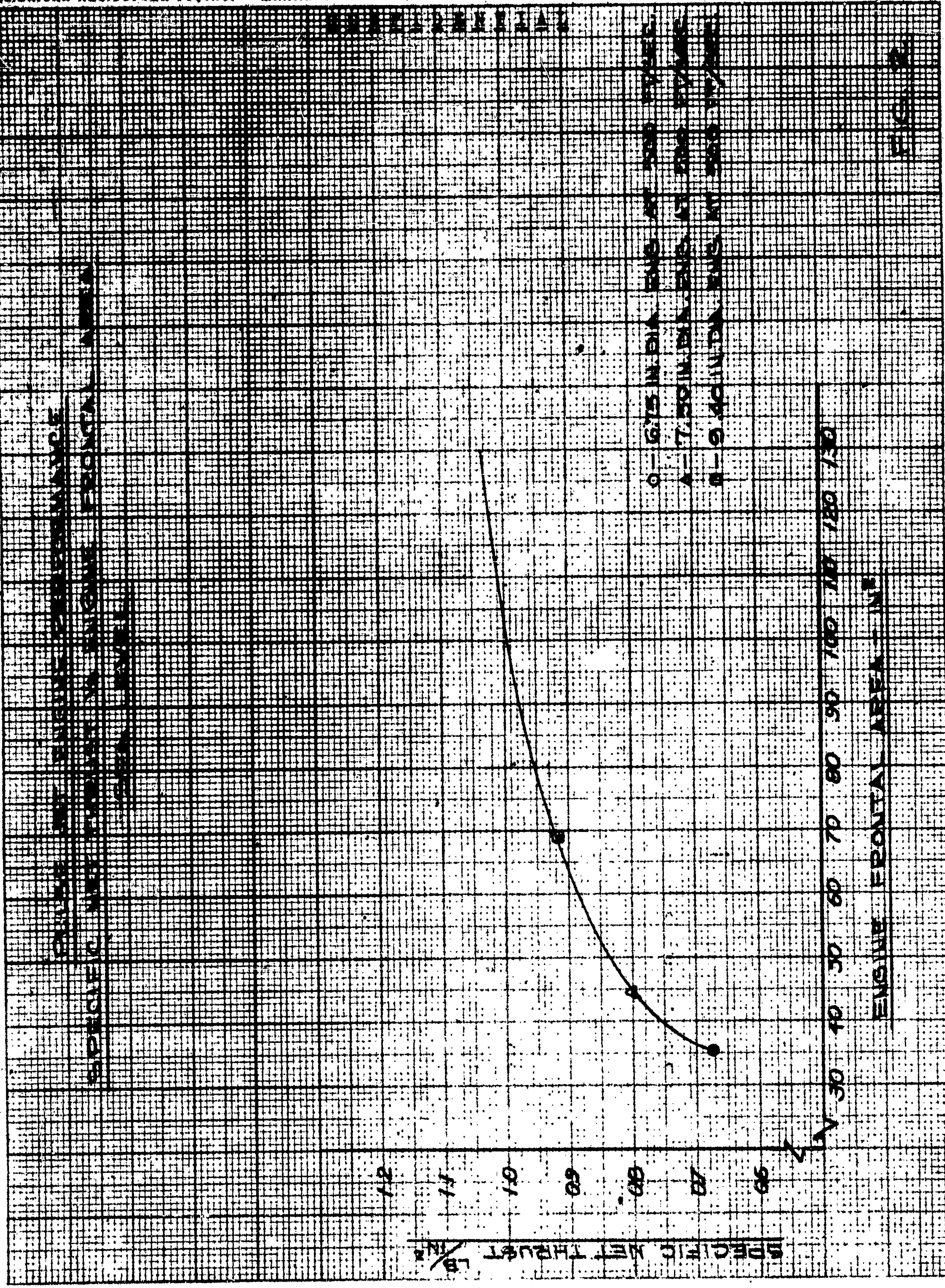

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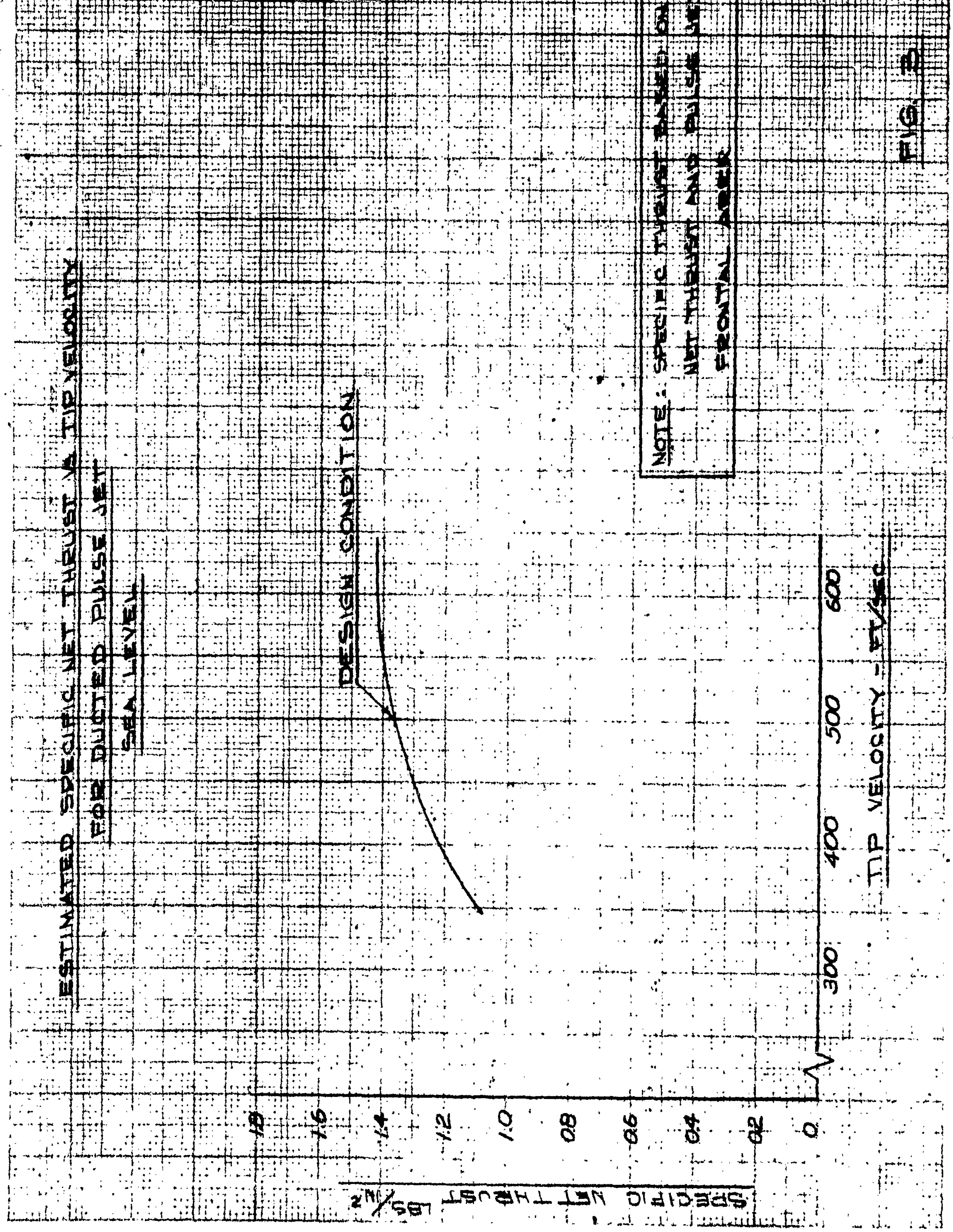

FIG. 3

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ESTIMATED PART THROTTLE CHARACTERISTICS

SPECIFIC FUEL CONSUMPTION VS. PERCENT OF PEAK THRUST AT SEA LEVEL

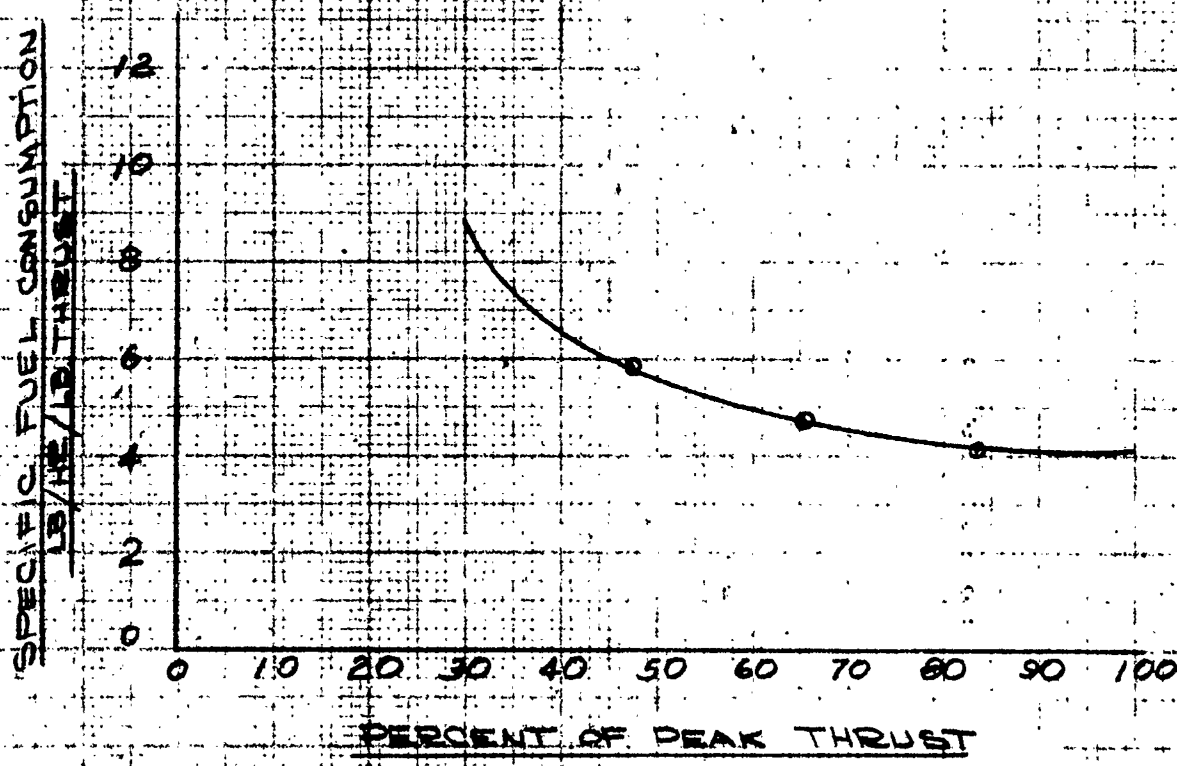

FIG. 4

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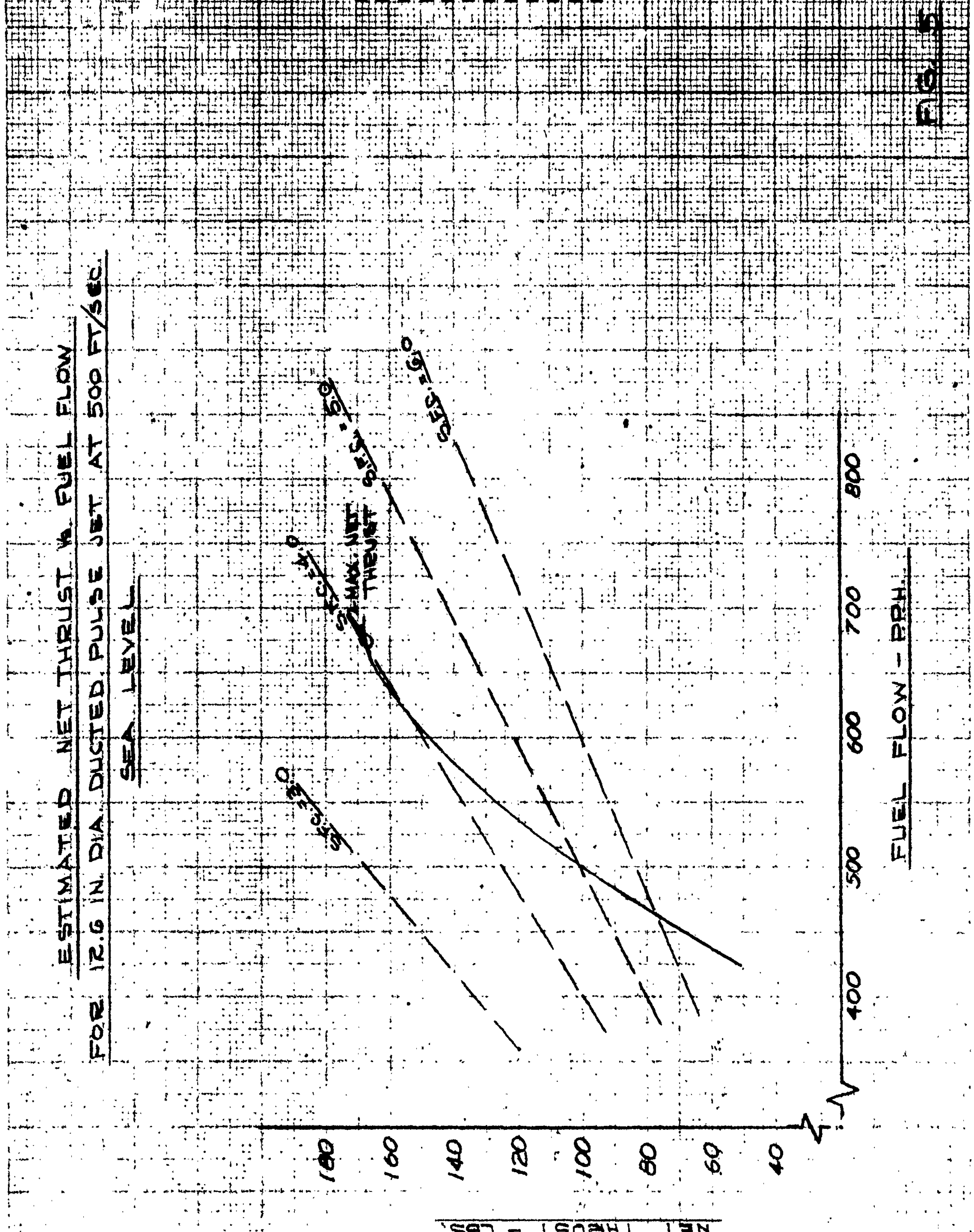

FIG. 5

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ESTIMATED PART THROTTLE IMPROVEMENT BY MEANS OF THRUST AUGMENTATION

SPECIFIC FUEL CONSUMPTION VS. PERCENT OF PEAK THRUST

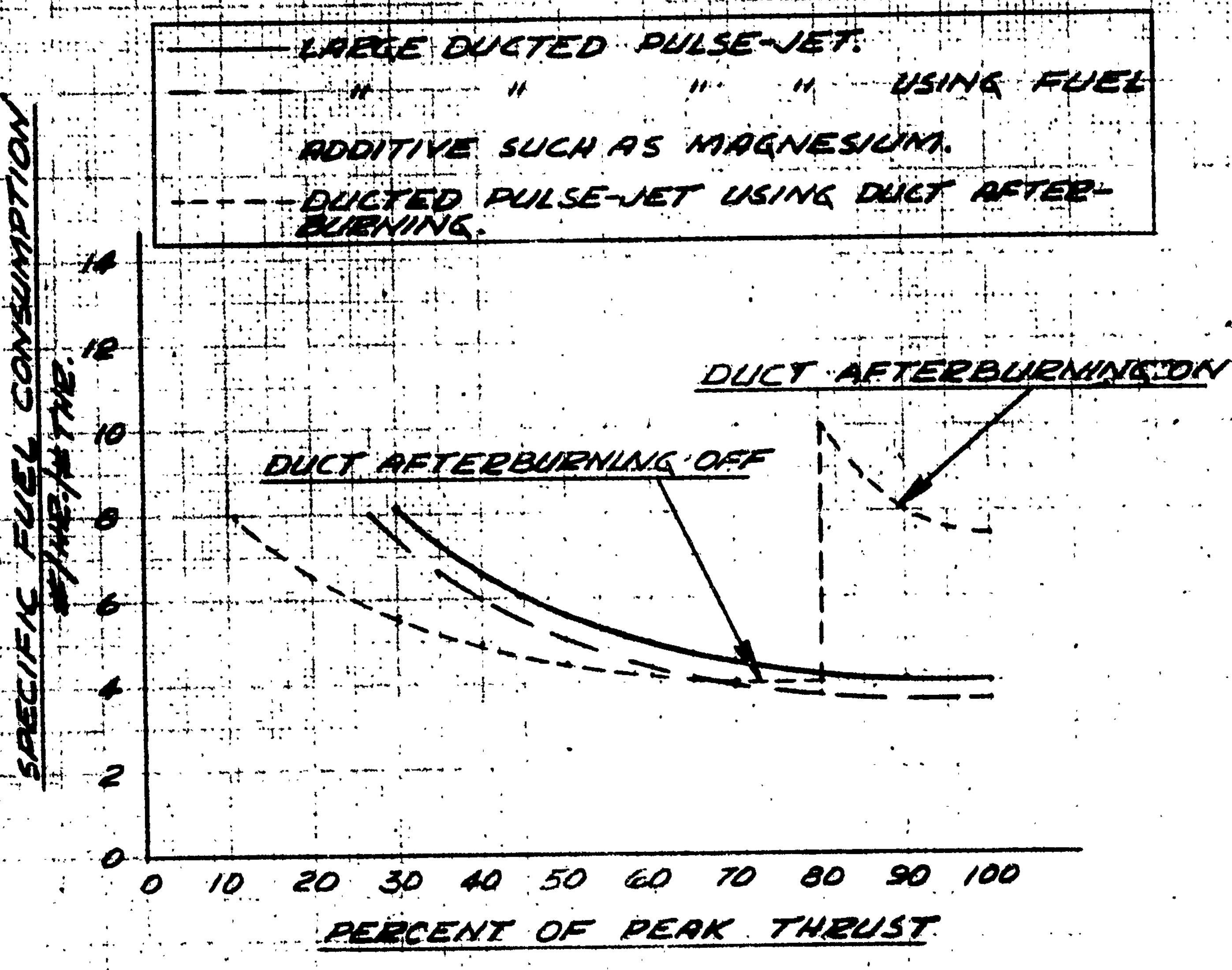
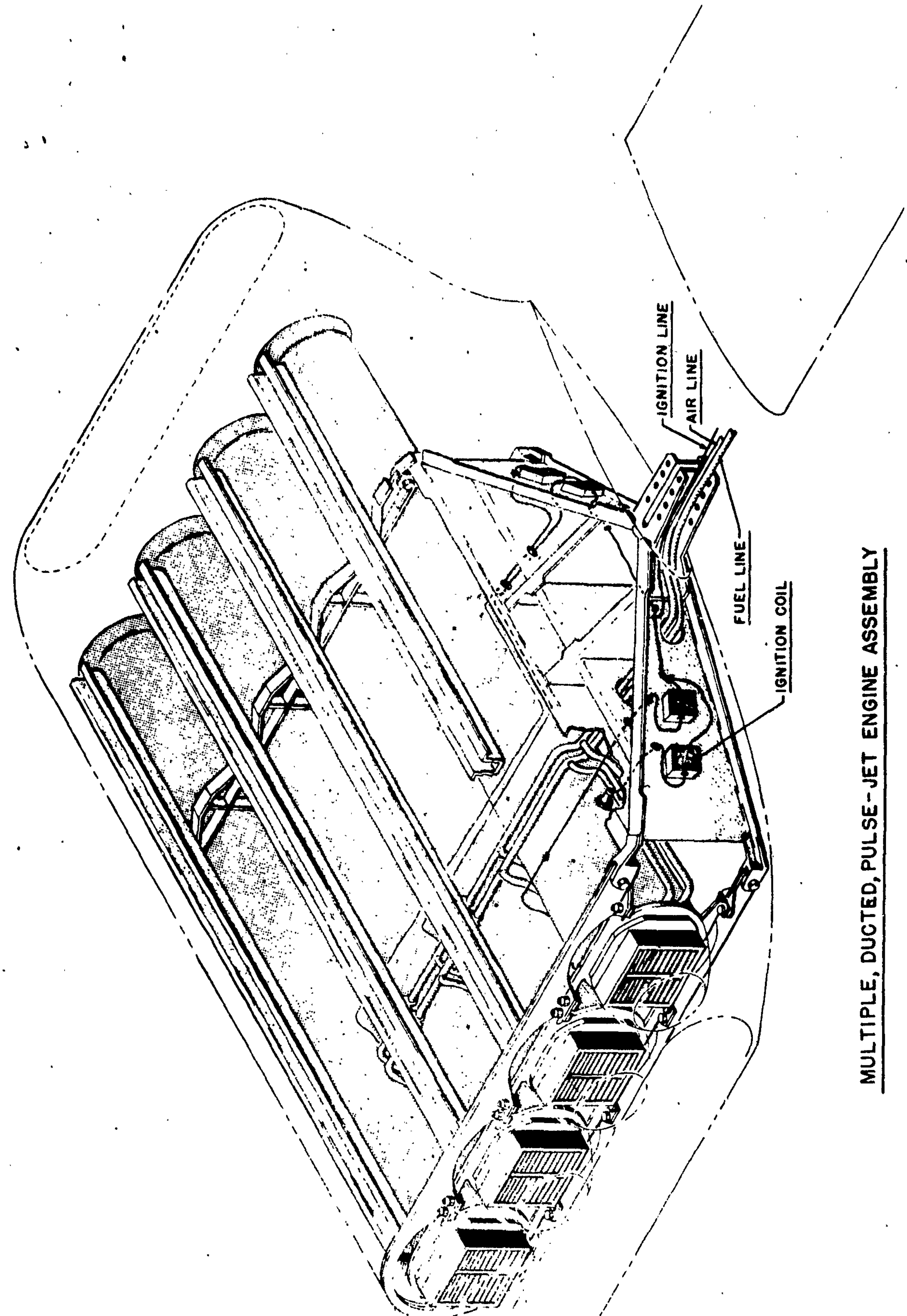


FIG. 6



MULTIPLE, DUCTED, PULSE-JET ENGINE ASSEMBLY

Figure 6a

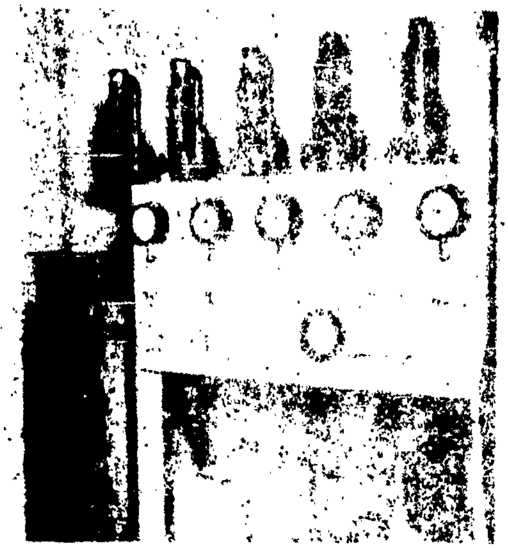


Figure 7

Figure 9

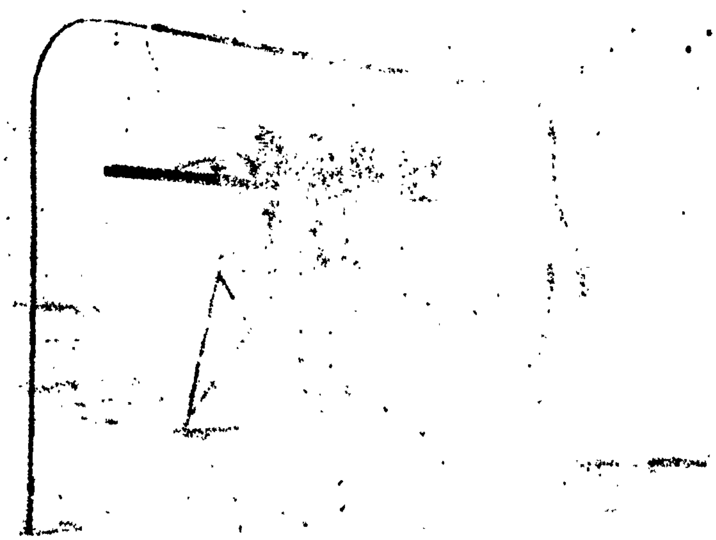


Figure 10

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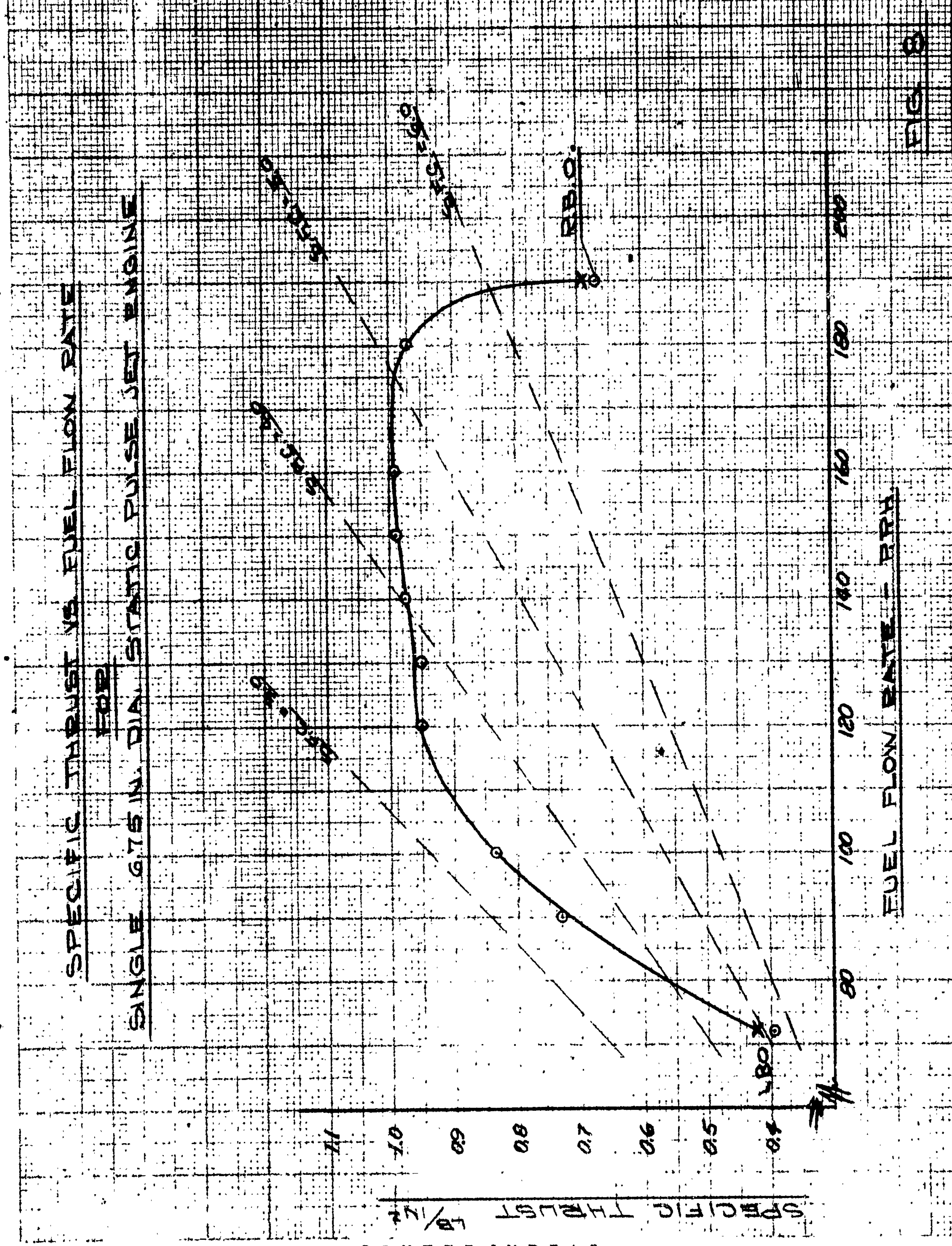

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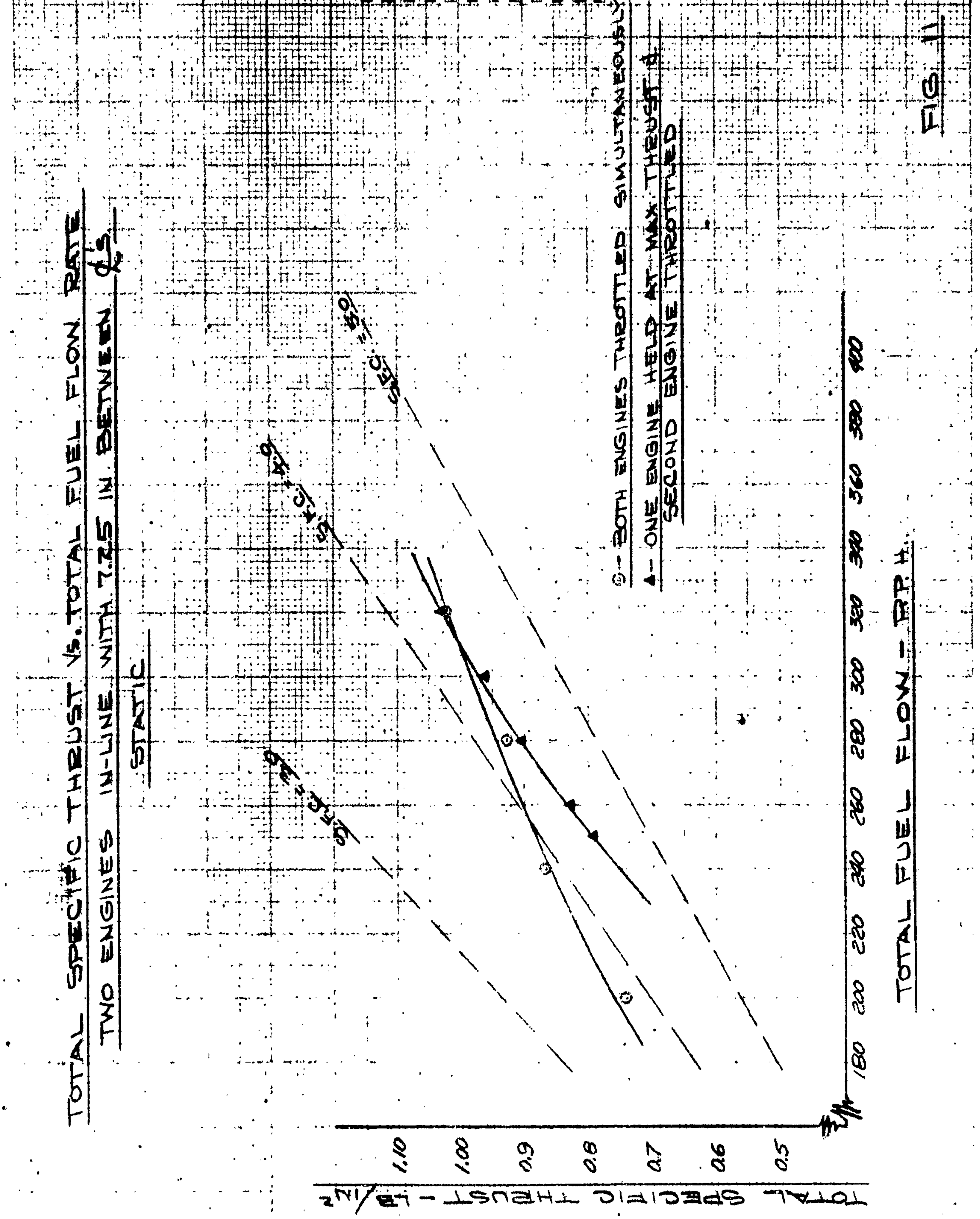

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TOTAL SPECIFIC THRUST VS. TOTAL FUEL FLOW RATE
THREE ENGINES IN-LINE WITH 7.75 IN. BETWEEN ℄'S
STATIC

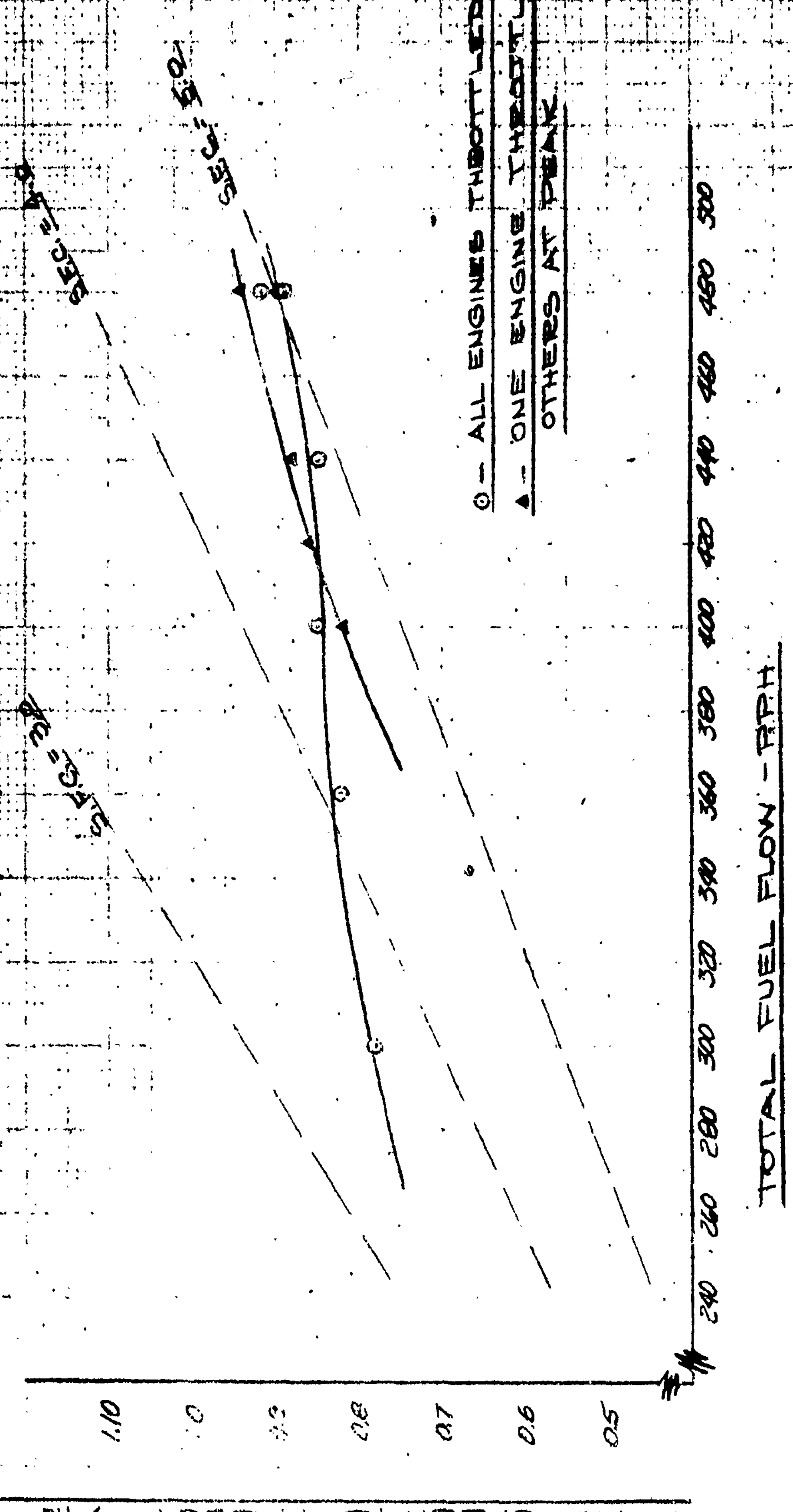

FIG. 12

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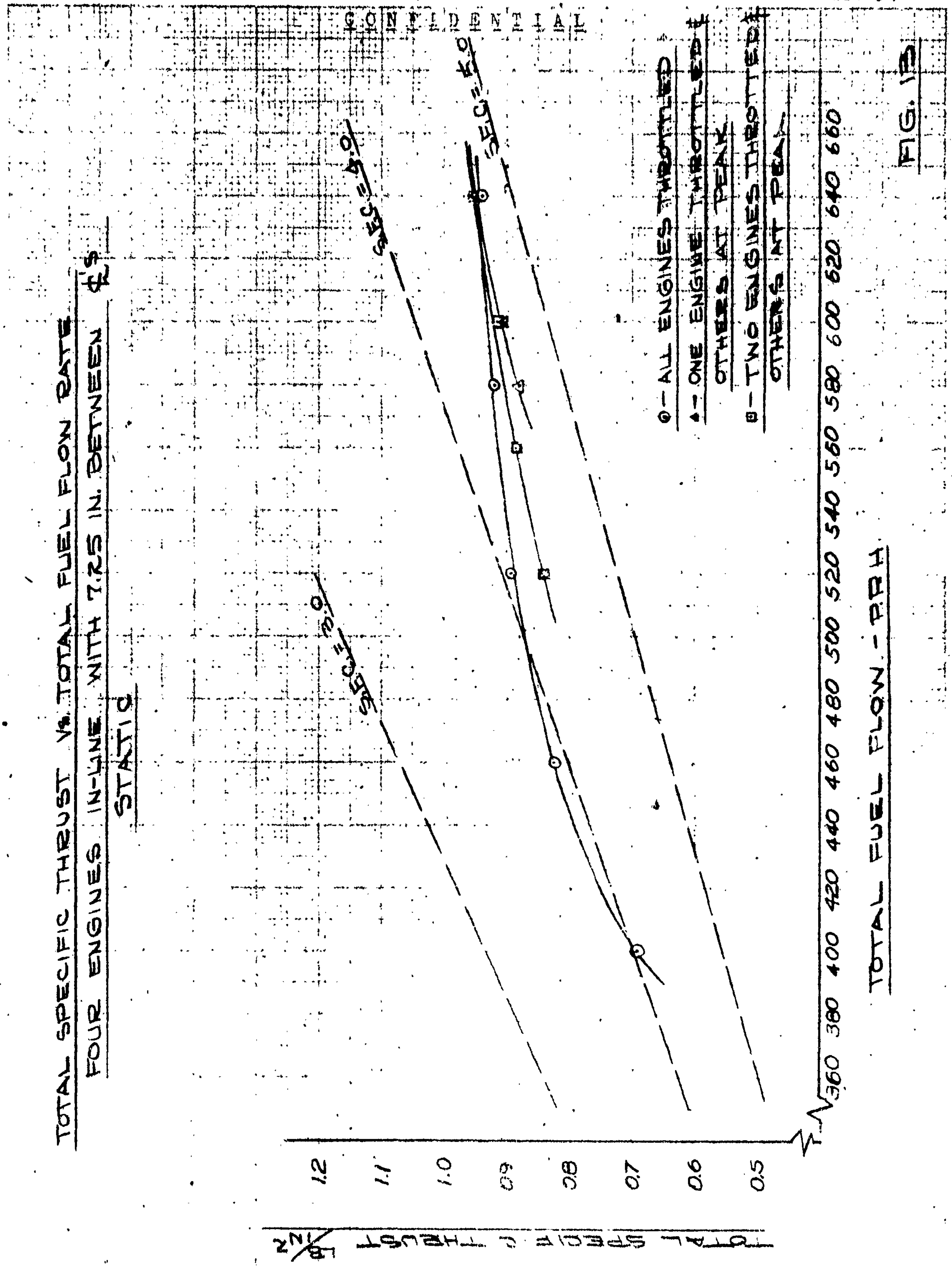
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TOTAL SPECIFIC THRUST VS. TOTAL FUEL FLOW RATE
FOUR ENGINES IN-LINE WITH 7.25 IN. BETWEEN ℄'S
STATIC
SEC = 3.0
SEC = 4.0
SEC = 5.0
⊙ - ALL ENGINES THROTTLED
▲ - ONE ENGINE THROTTLED, OTHERS AT PEAK
⊡ - TWO ENGINES THROTTLED, OTHERS AT PEAK
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
TOTAL SPECIFIC THRUST LB/IN²
360 380 400 420 440 460 480 500 520 540 560 580 600 620 640 660
TOTAL FUEL FLOW - PPH
FIG. 13

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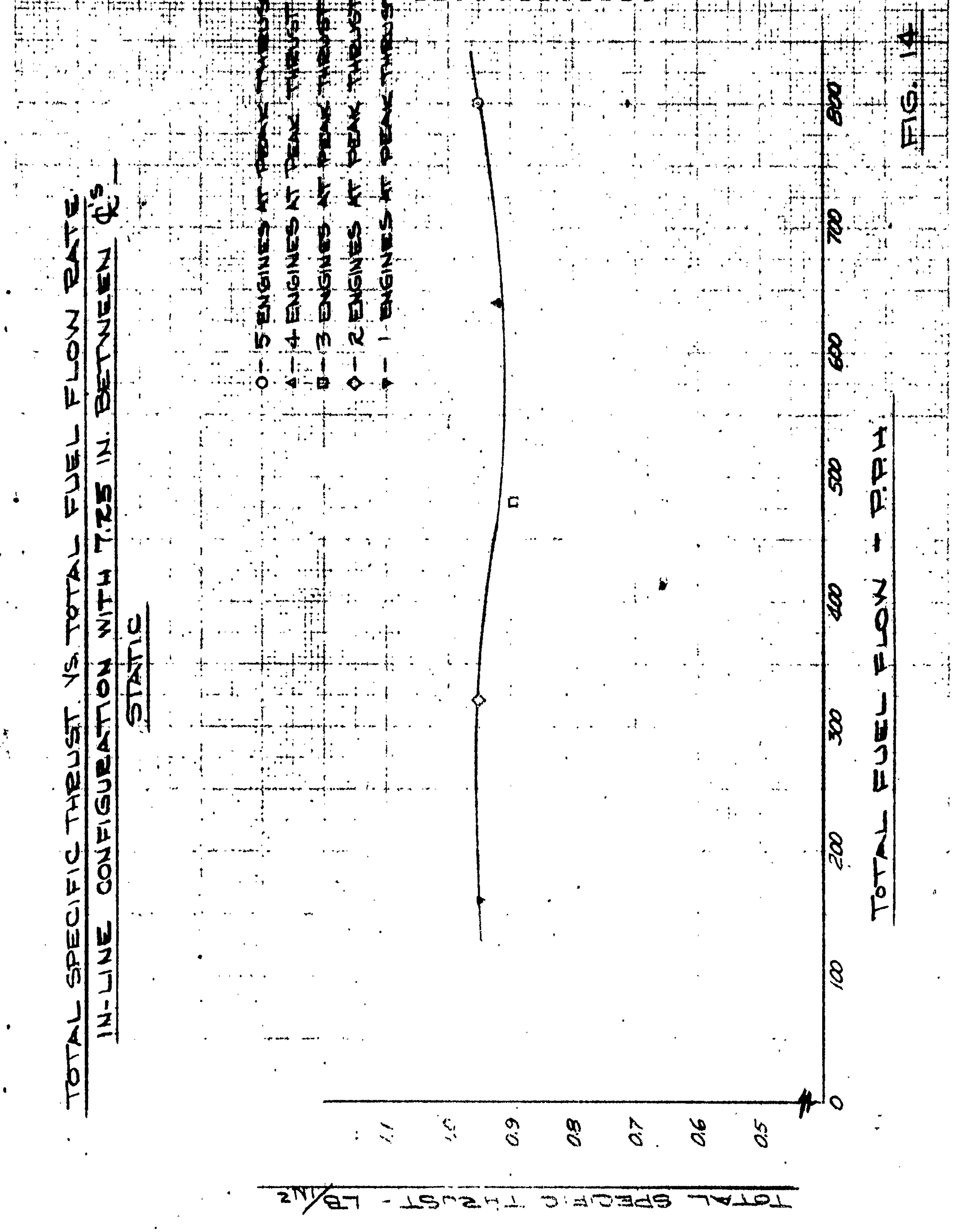

FIG. 14

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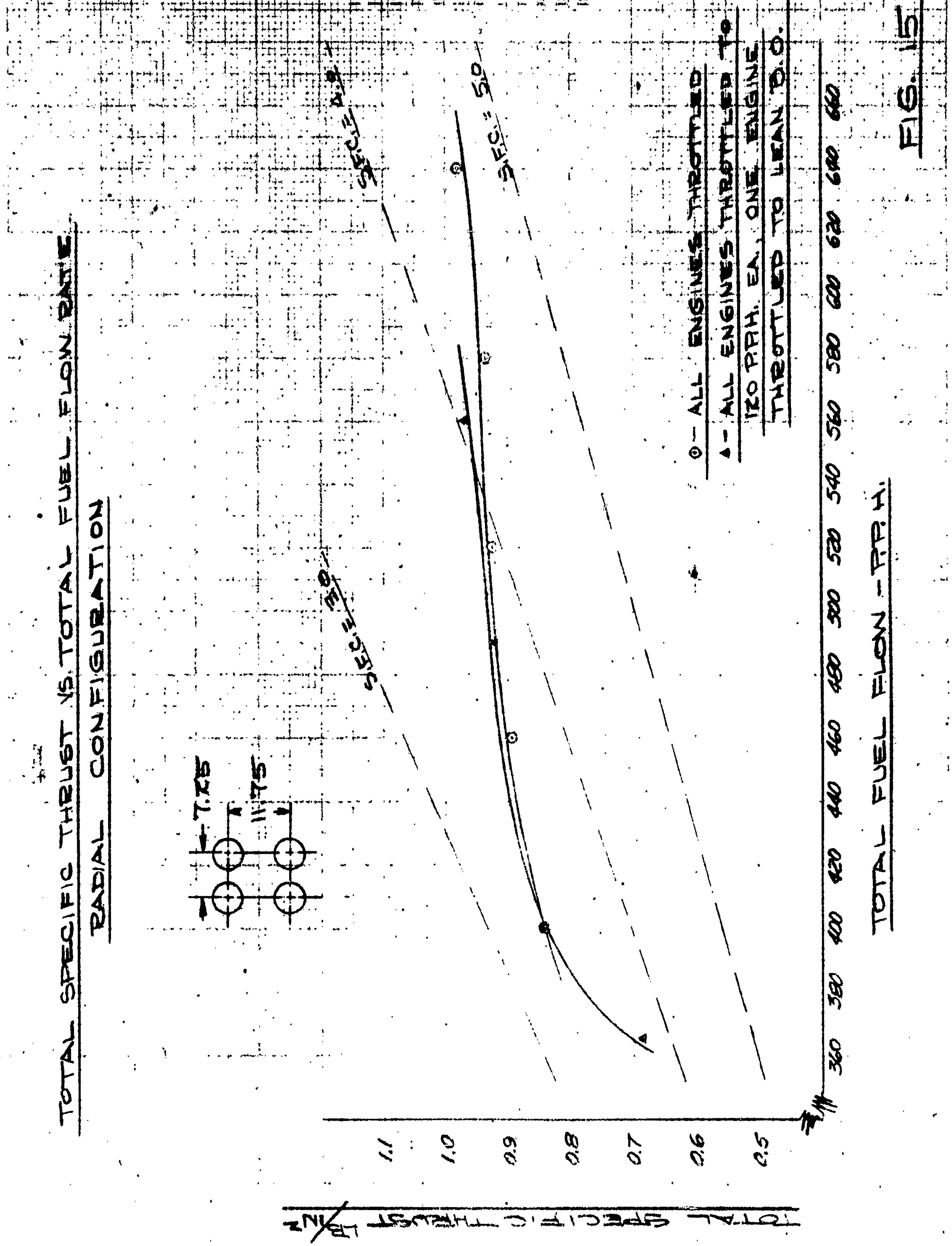

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90° EXHAUST ENGINE STATIC TESTS

CONFIGURATION NO II

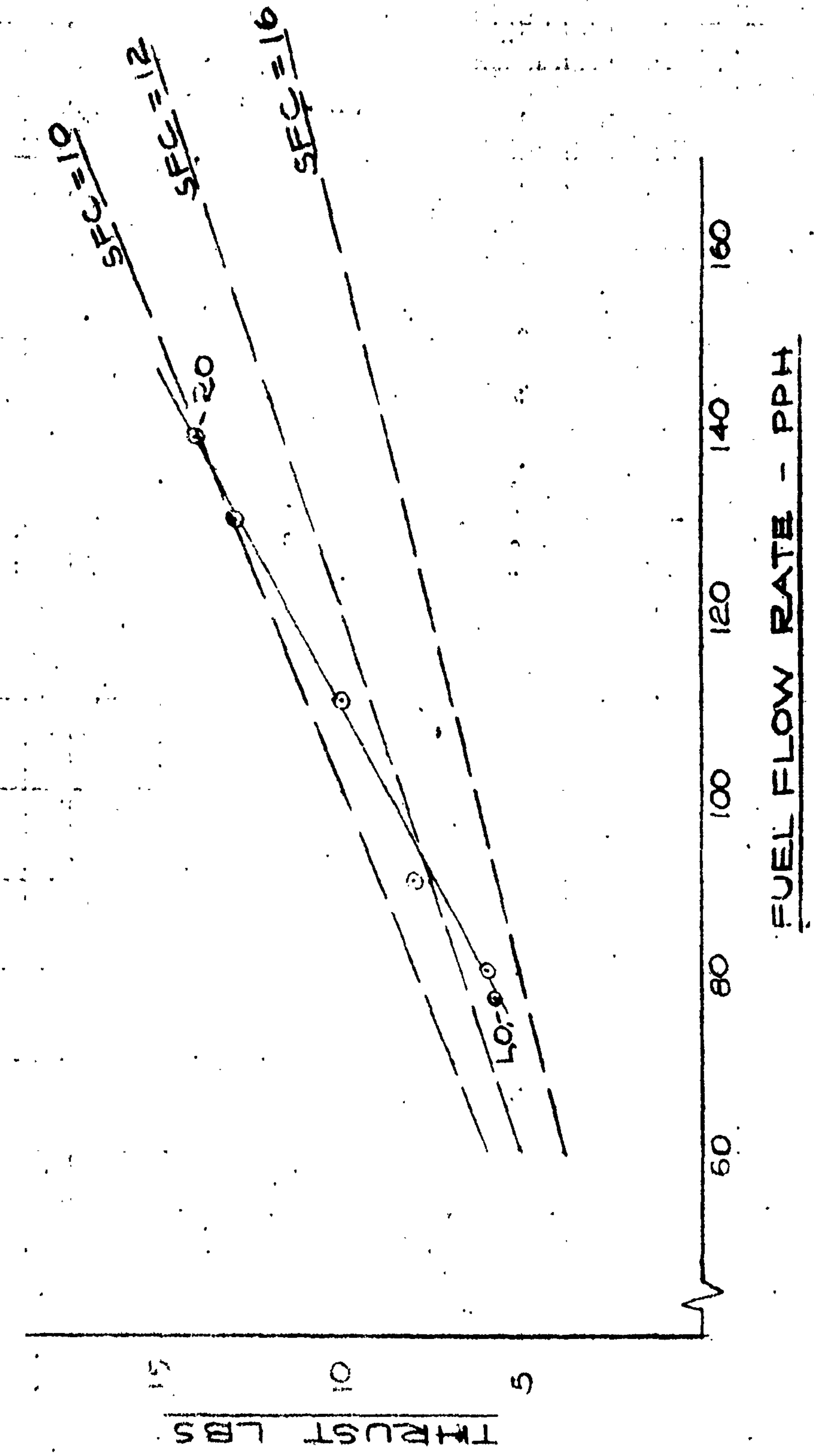

FIG. 16.

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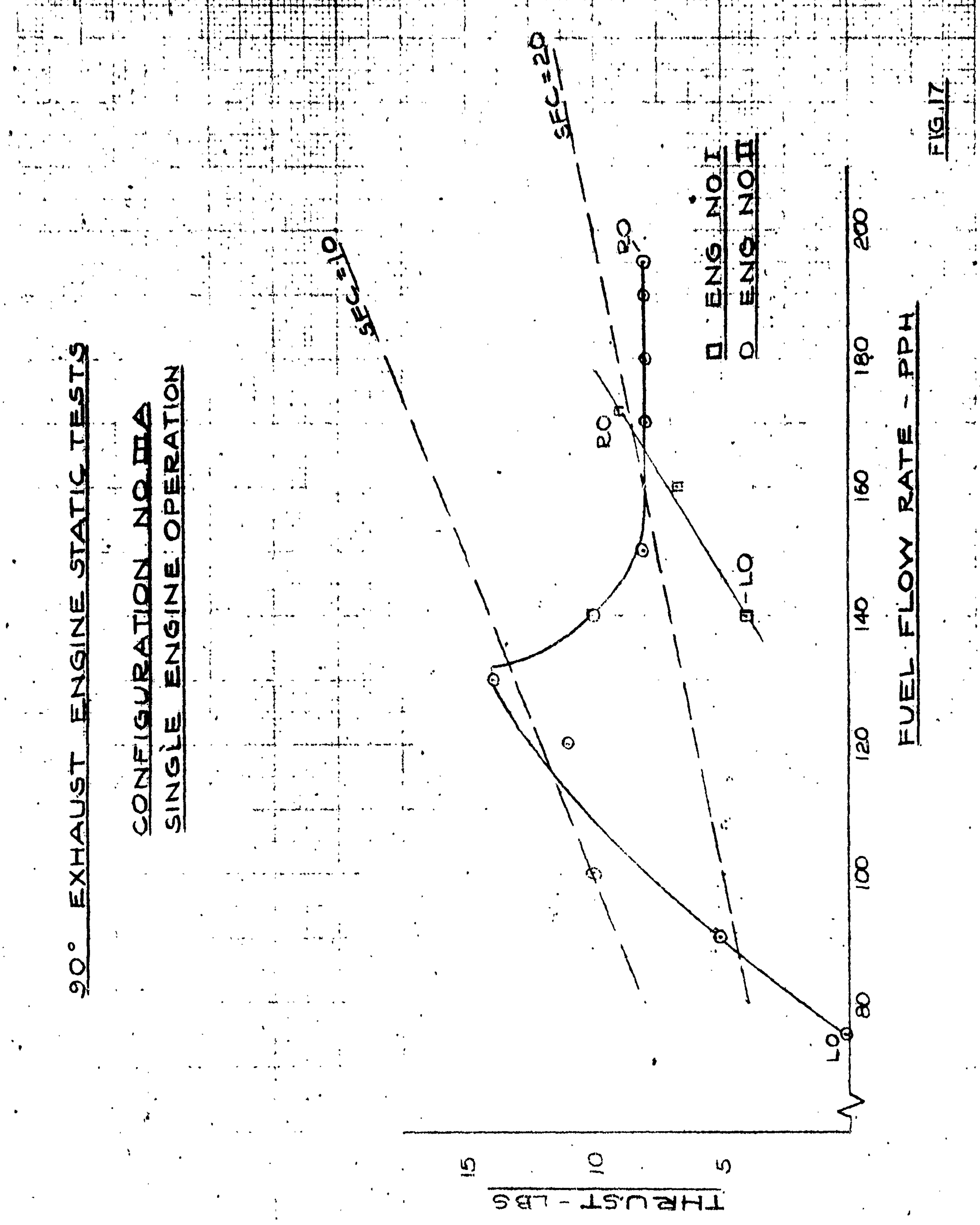
C O N F I D E N T I A L



C O N F I D E N T I A L

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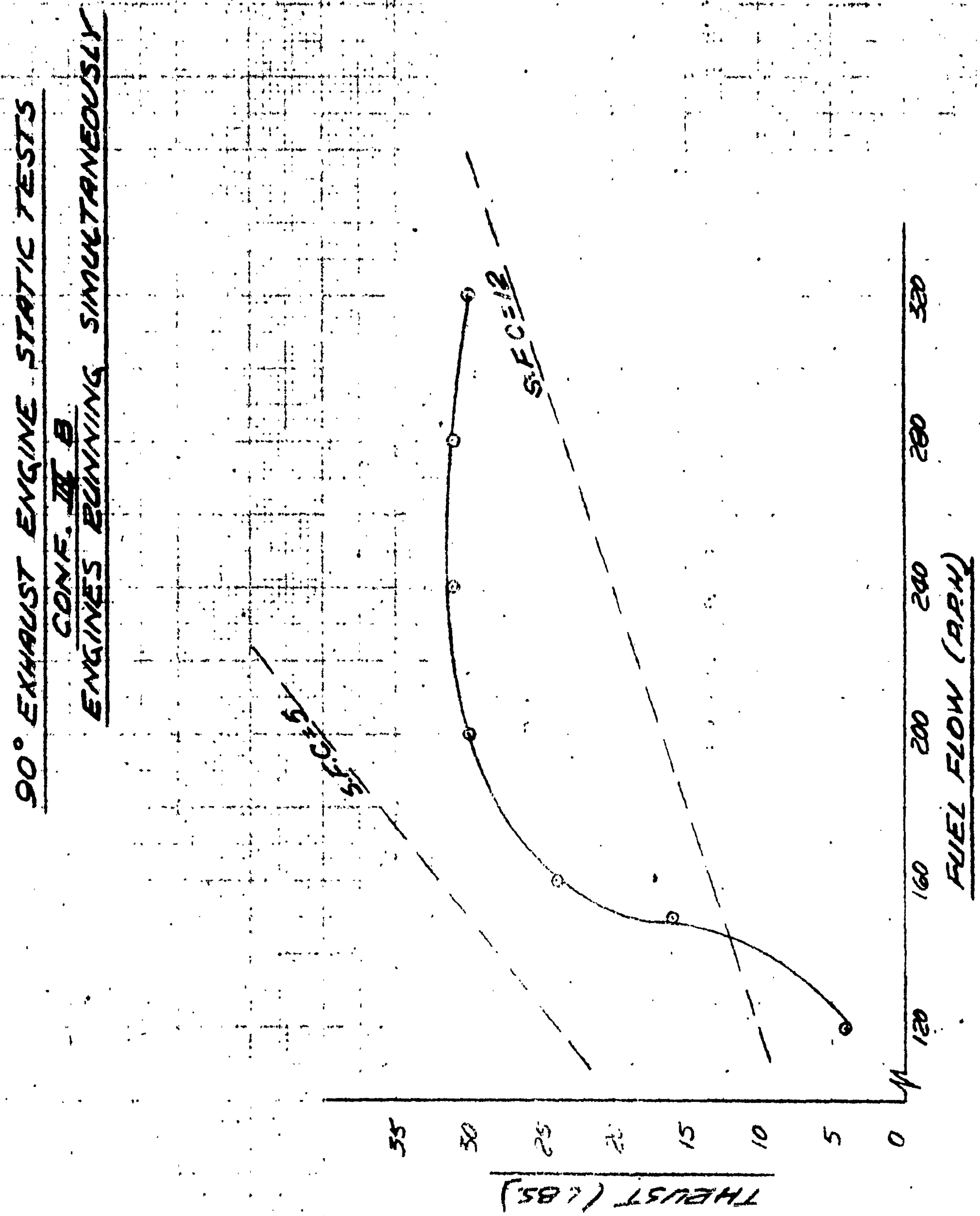

FIG. 18

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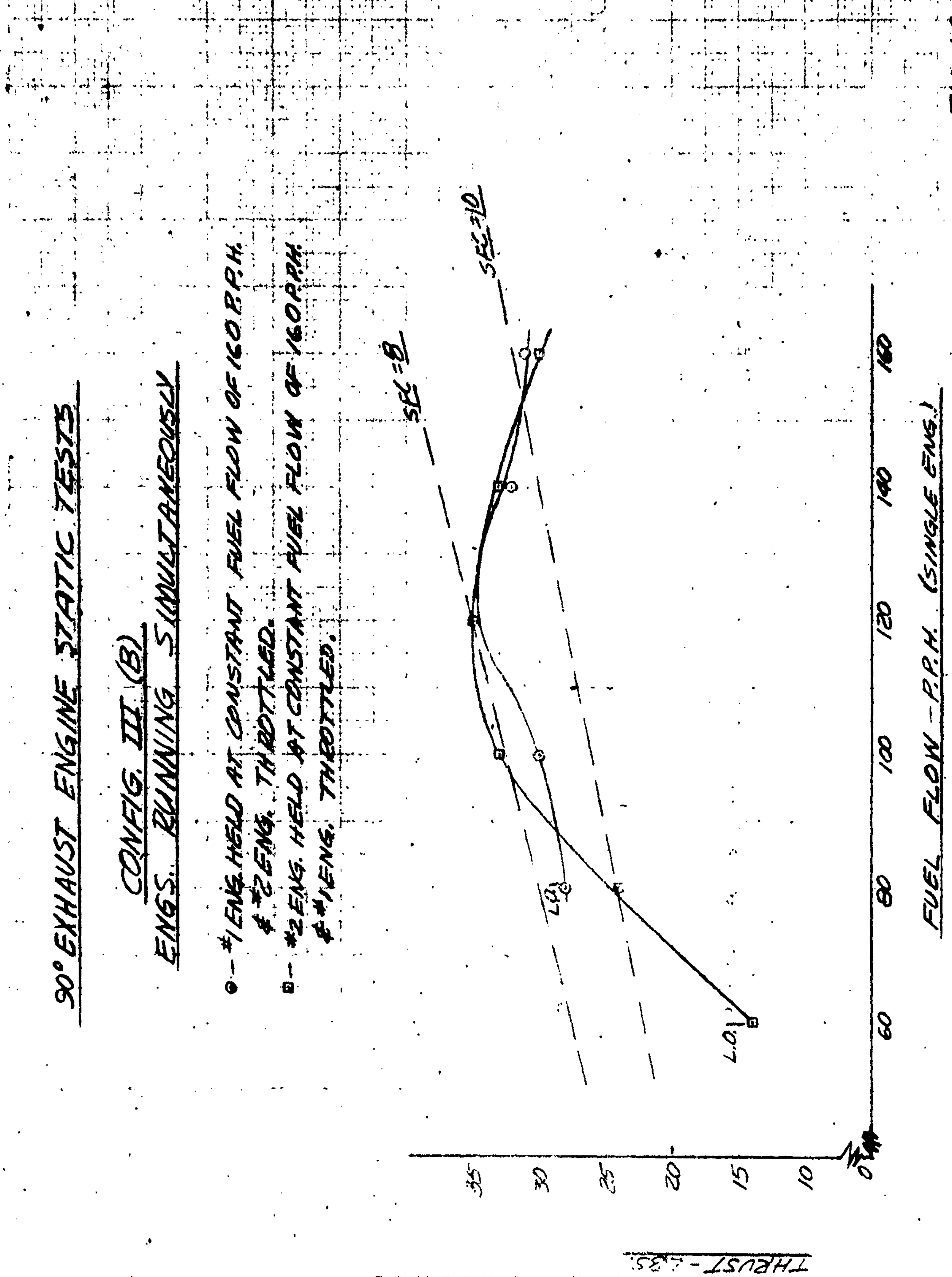

FIG. 19

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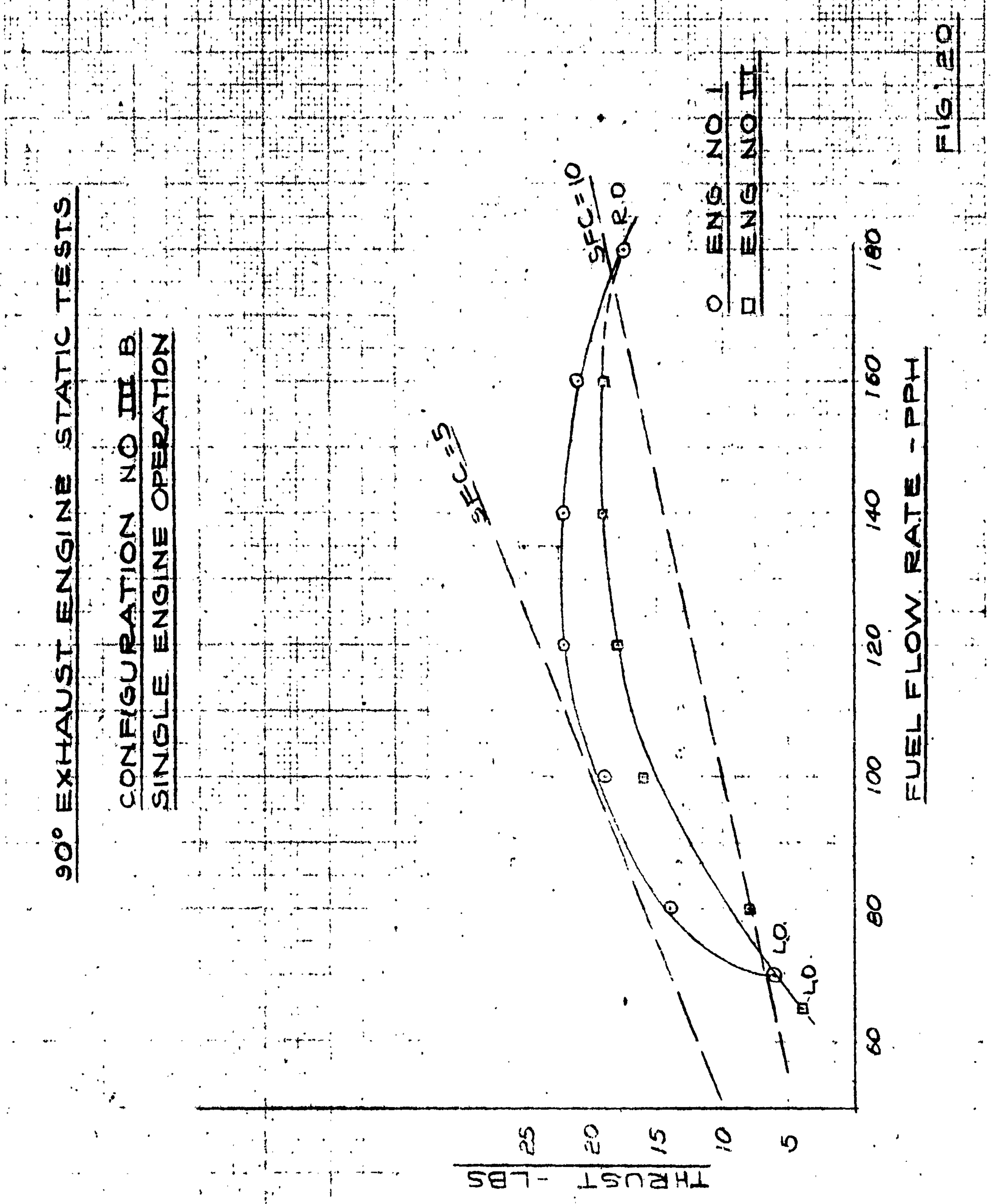

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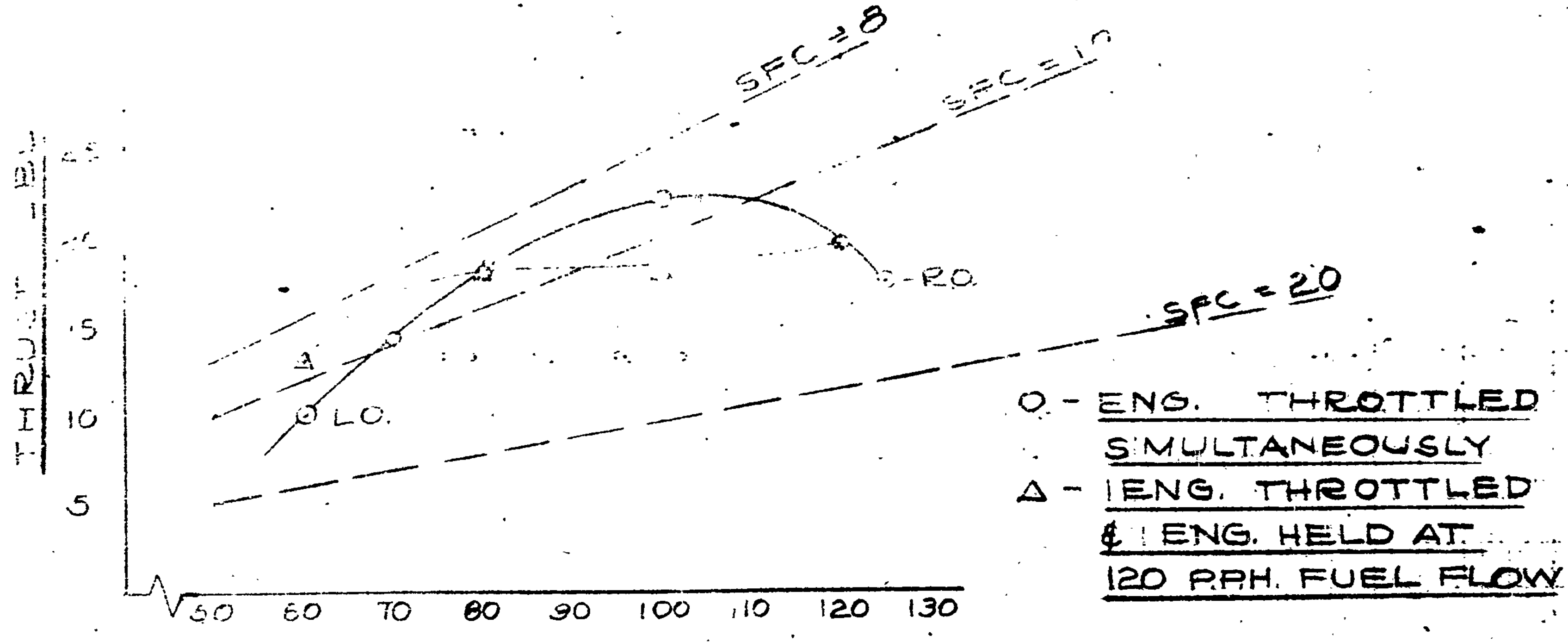
90° EXHAUST ENGINE STATIC TESTS

CONFIGURATION NO III (c)
BOTH ENGINES RUNNING



FUEL FLOW RATE - PPH
FOR SINGLE ENGINE

FIG. 21

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90° EXHAUST ENGINE STATIC TESTS

CONFIGURATION NO III (c)

ENGINES RUNNING SEPARATELY

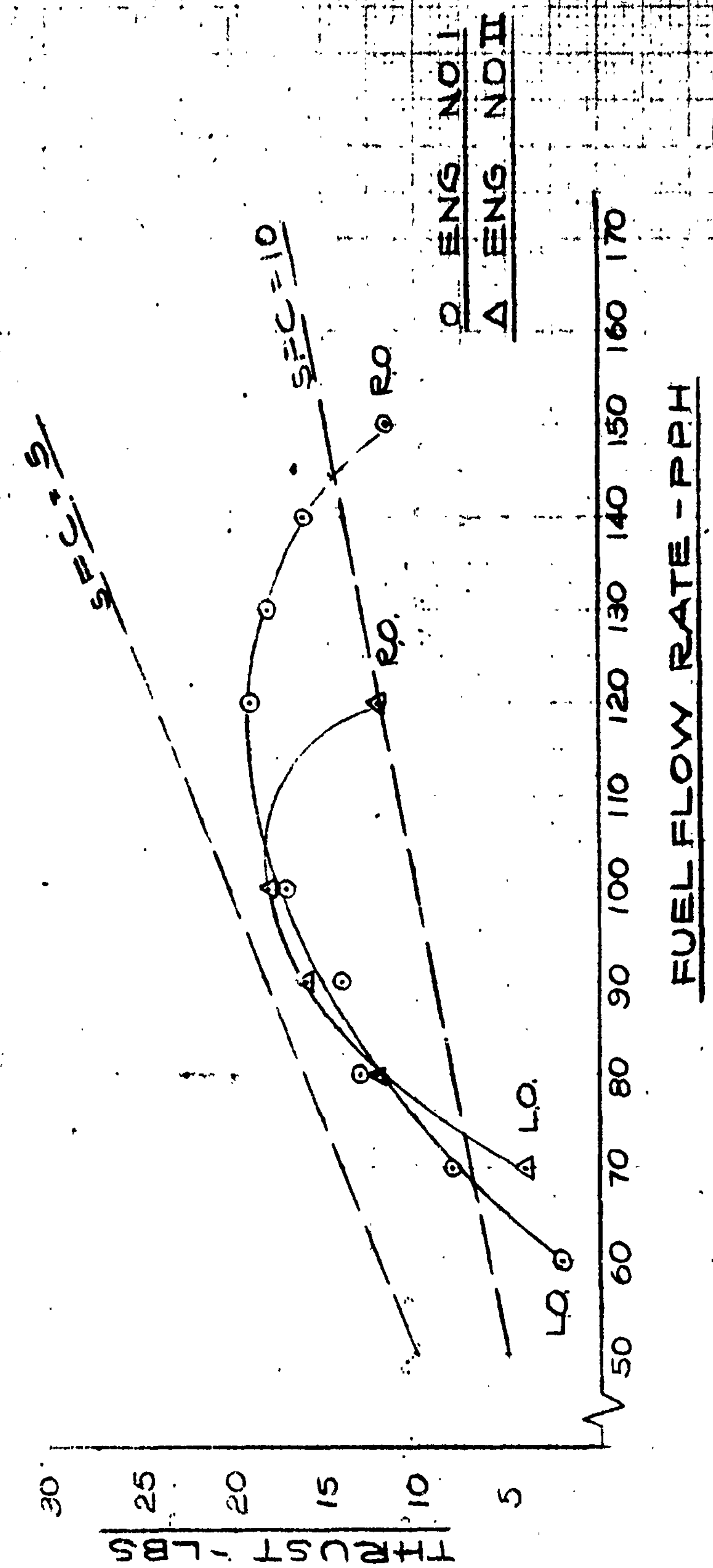
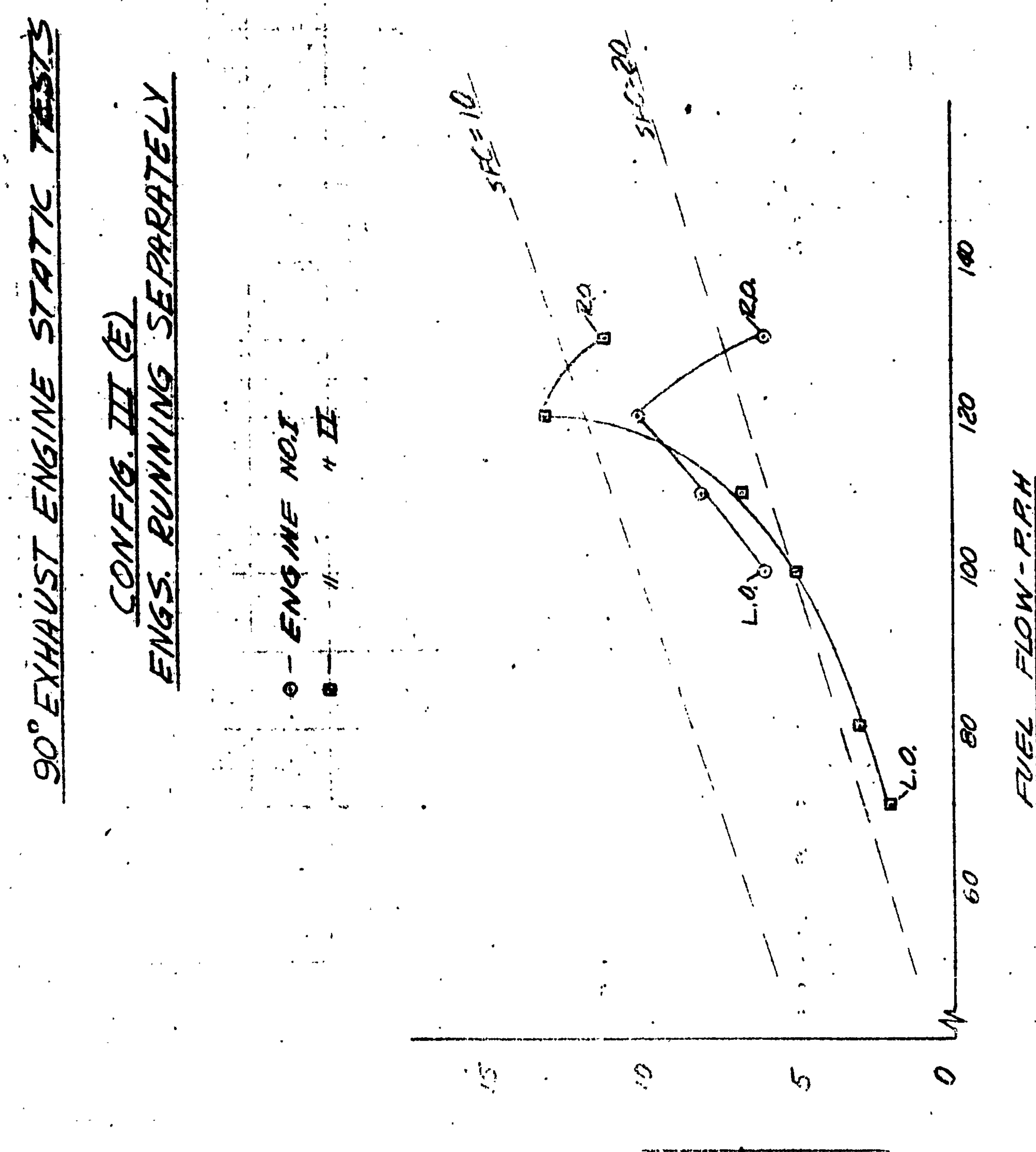


FIG. 22

FIG. 23


90° EXHAUST ENGINE STATIC TESTS
CONFIG. III (E)
ENGS. RUNNING SEPARATELY
⊙ - ENGINE NO. I
⊡ - " " II
SFC = 10
SFC = 20
R.O.
R.O.
L.O.
L.O.
FUEL FLOW - P.P.H.
60
80
100
120
140
THRUST - LBS.
0
5
10
15

CONFIDENTIAL

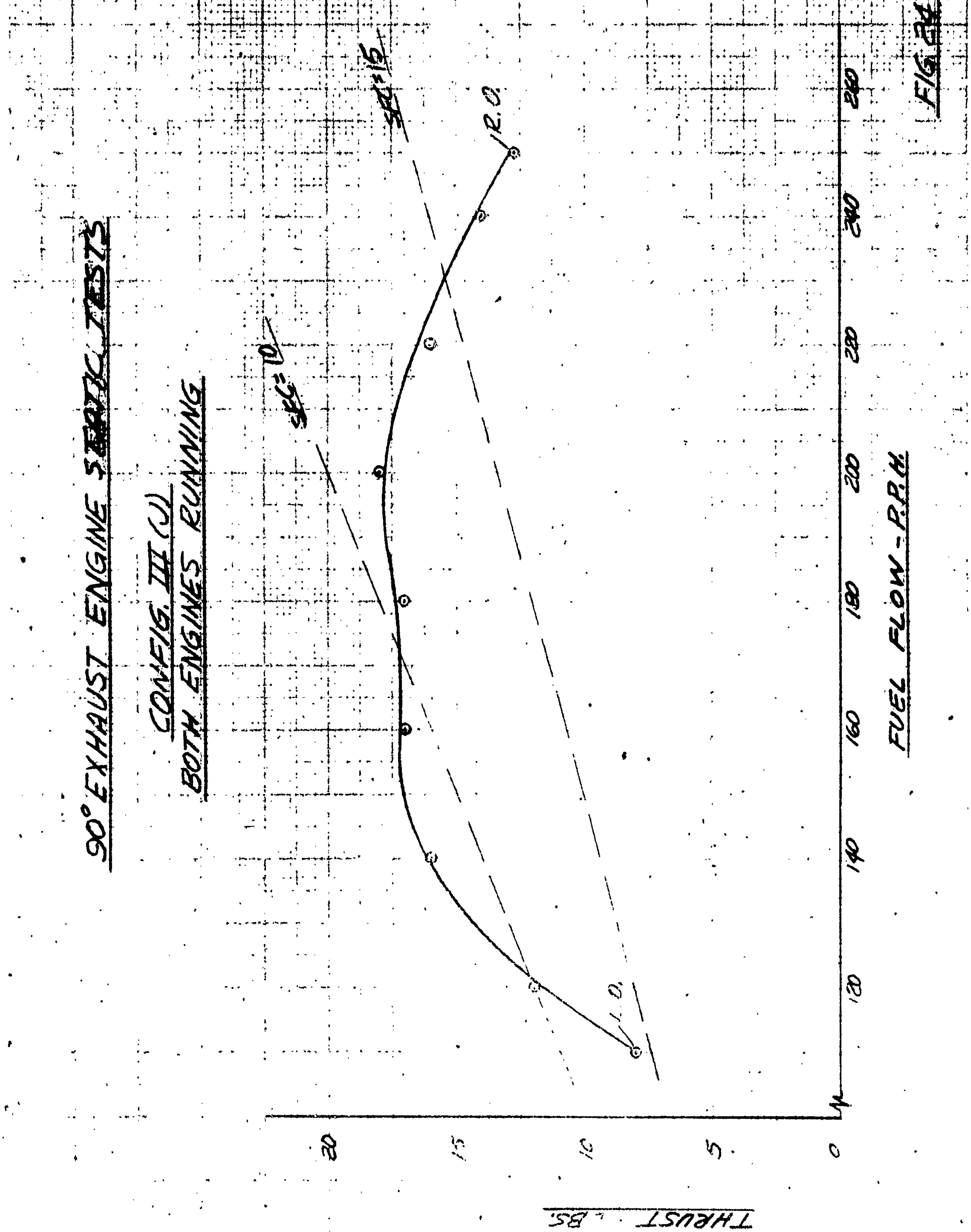


FIG 24

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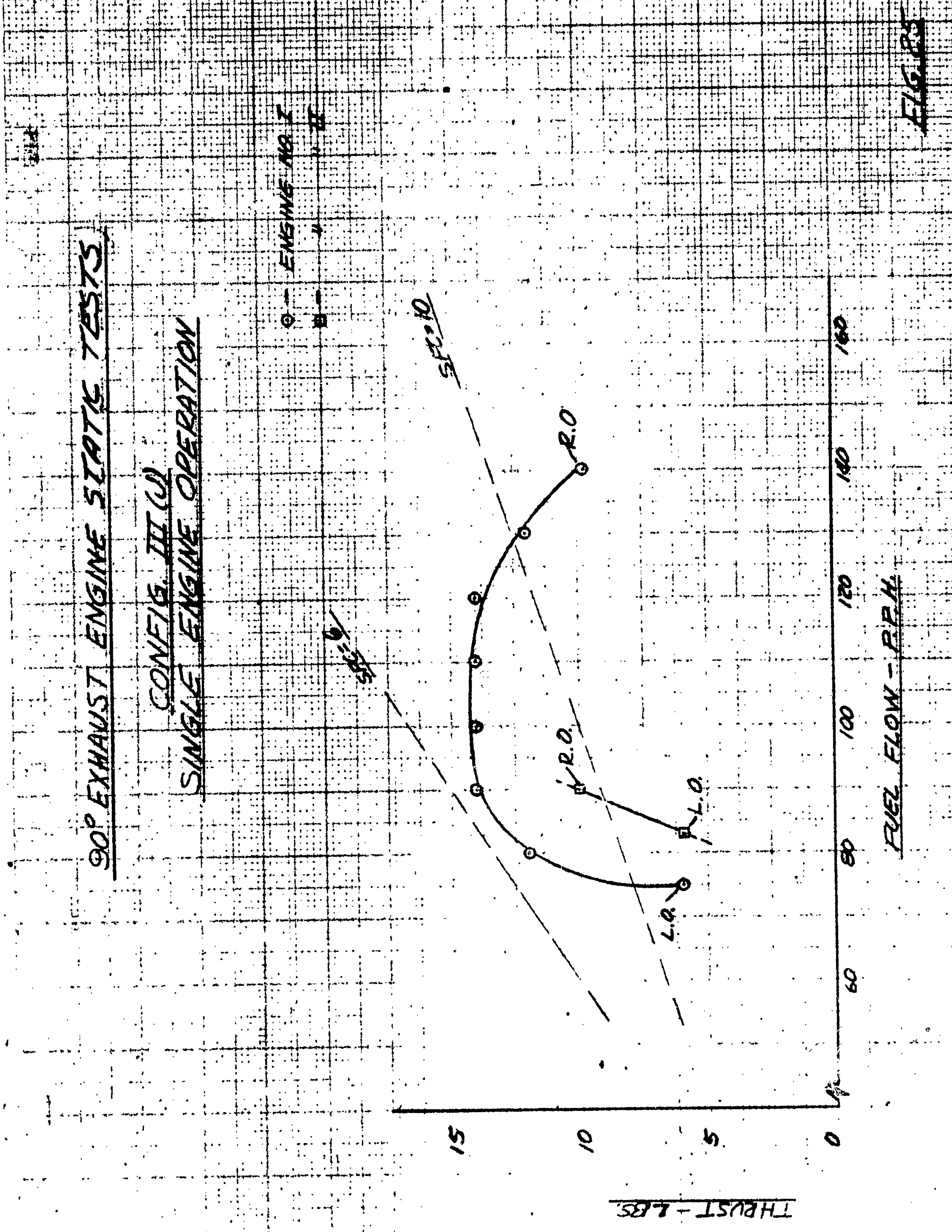
90° EXHAUST ENGINE STATIC TESTS
CONFIG. II (U)
SINGLE ENGINE OPERATION
⊙ - ENGINE NO. I
⊡ - " " II
SFC = 10
SFC = 6
R.O.
L.O.
R.O.
L.O.
THRUST - LBS.
0
5
10
15
60
80
100
120
140
160
FUEL FLOW - PPH

FIG. 25

Figure 26

Figure 27

Figure 28

Figure 29

Figure 30

Figure 31

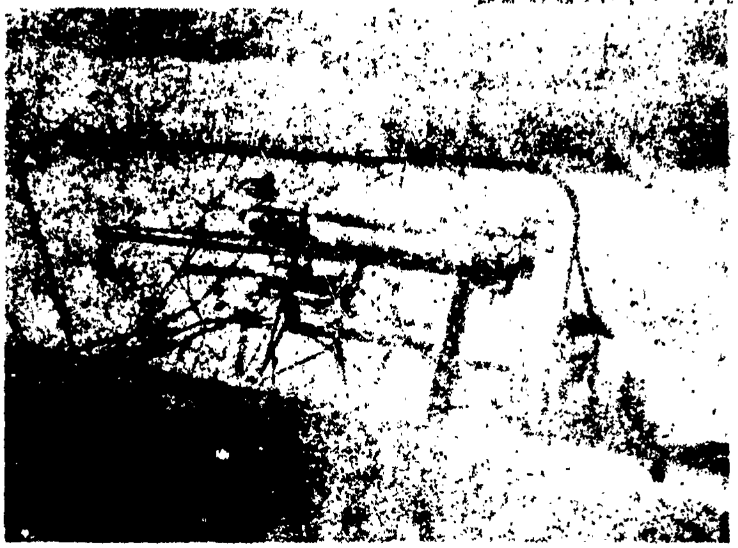

Figure 32

Figure 33

Figure 34